이 학 박 사 학 위 논 문

Studies on Poly(N-Heterocyclic Carbene) and Base Catalysis for Organic Reactions

고분자 N-헤테로고리 카빈과 염기촉매를 이용한 유기반응의 연구

2017년 2월

서울대학교 대학원

화학부 무기화학전공

서 의 령

Studies on Poly(N-Heterocyclic Carbene) and Base Catalysis for Organic Reactions

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By

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지도 교수 정 영 근

이 논문을 이학박사 학위논문으로 제출함

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서 의 령

서 의 령의 박사학위논문을 인준함

2016 년 12월

위 원 장 _____ **(인)**

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Studies on Poly(N-Heterocyclic Carbene) and Base Catalysis for Organic Reactions

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Part I. Poly (N-heterocyclic carbene) catalyzed reactions

Chapter 1. Poly (4-vinylimidazolium) iodides: a highly recyclable organocatalyst precursor for benzoin condensation reaction

The development of highly efficient, recyclable poly(4-vinylimidazolium) iodides (**2**) for the benzoin condensation reaction under mild reaction conditions is discussed: poly(4-vinyl N-heterocyclic carbene)s (**3**) obtained from **2** showed higher catalytic activity than monomeric 4-vinyl N-heterocyclic carbene and could be successfully recovered and reused over seven times without loss of performance.

Chapter 2. Poly (4-vinylimidazolium)s/ Diazabicyclo[5.4.0]undec-7-ene/ Zinc(II) Bromide-Catalyzed Cycloaddition of Carbon Dioxide to Epoxides

Poly(4-vinylimidazolium)s (**2**) with diazabicyclo[5.4.0]undec-7-ene (DBU) and zinc bromide ($ZnBr_2$) are used as a highly efficient catalyst for chemical fixation of carbon dioxide. This catalytic system has been applied for preparation of cyclic carbonates from terminal epoxides and carbon dioxide. Many functional groups are well tolerated in the reactions. Moreover, the catalytic system was found to catalyze the conversion of more sterically congested epoxides which are generally considered challenging substrates for fabricating the cyclic organic carbonates. In addition, the disubstituted epoxides are found to react with retention of configuration. The polymer precatalyst is easily recovered and reused.

Keywords. Poly(4-vinylimidazolium)s/ Organocatalysis/ Recyclable/ Polymers/ Benzoin/ Carbon dioxide fixation/ Cyclic carbonate

Part II. Base-catalyzed organic reactions

Chapter 1. Potassium Phosphate-Catalyzed One-pot Synthesis of 3-Aryl-2-oxazolidinones from Epoxides, Amines, and an Atmospheric Carbon Dioxide

Potassium phosphate was found to be a highly active catalyst in the three-component

cycloaddition of amine, epoxide, and carbon dioxide in DMF at ambient temperature to form 3-aryl-2-oxazolidinones. Atmospheric CO_2 and a broad range of amines were employed in this transformation. Aryl isocyanate and 1,2-aminoalcohol were generated in situ as key intermediates. This one-pot reaction is applicable to a variety of terminal aryl epoxides and amines. The key advantages are high yields, simple work-up, inexpensive catalyst, and a practical ten gram-scale synthesis.

Chapter 2. Base-catalyzed one-pot synthesis of unsymmetric fluorenes from aromatic ortho-dialdehydes and 1,3-dicarbonyl compounds

A synthetic route for the preparation of unsymmetrically polysubstituted fluorenes was developed via the base-catalyzed one-pot domino reactions of aromatic ortho-dialdehydes with 1,3-dicarbonyl compounds. This protocol provides an expeditious access to indene-fused polycyclic aromatic hydrocarbons such as benzo[b]fluorene and 13H-indeno[1,2-b]anthracene skeletons.

Keywords. Base-catalyzed/ Potassium Phosphate/ One-pot reaction/ Domino reaction/ Scalability/ Unsymmetric fluorenes/ Carbon dioxide fixation/ Oxazolidione

Student Number: 2013-30904

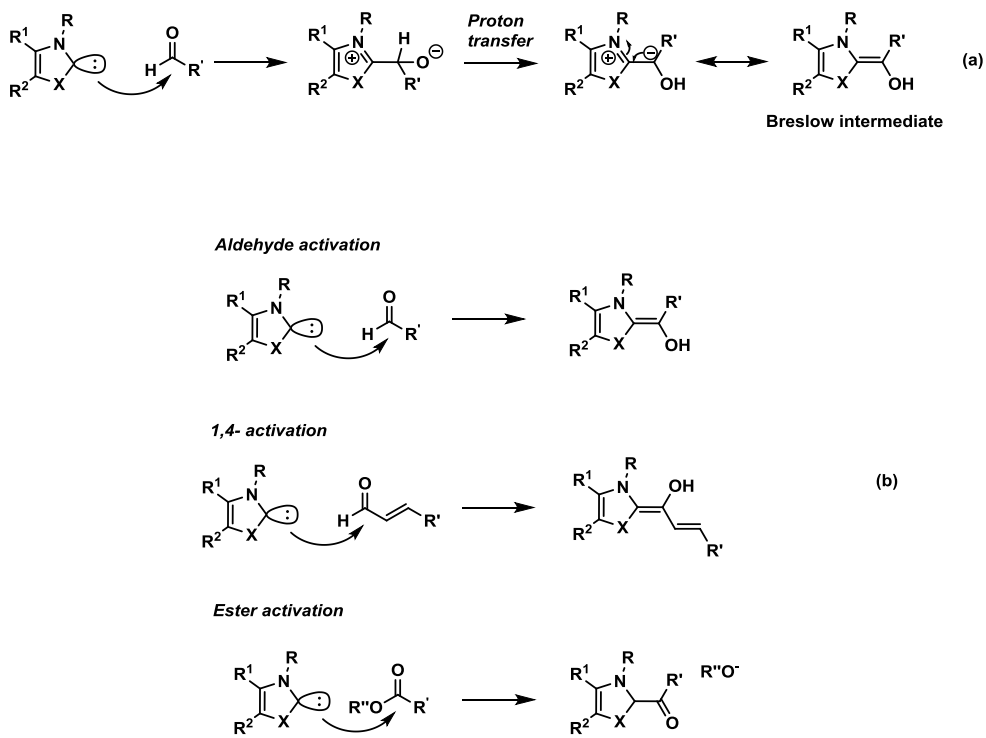
Part I.

Poly (N-heterocyclic carbene)-catalyzed reactions

General

Research background

N-Heterocyclic carbenes (NHCs) are the most valuable structures that have been used for versatile ligands for transition metals as well as powerful organocatalysts as they exhibit strong basicity.[1] This is due to their unique electronic and steric properties that can be finely tuned through variation of their substituted pattern, offering many possibilities to modulate their reactivity. In this regard, tremendous studies using NHCs have been developed.[2] This part will focus on the development of new polymeric NHCs as an organocatalyst.



Scheme 1. Breslow intermidatate (a) and substrate activation by NHCs (b)

NHC-mediated organocatalyzed reactions are usually carried out under relatively mild conditions. Becasuse the nucleophilic addition of NHCs onto carbonyl groups leads to the 'Breslow intermediate'[3] which electrophilic carbonyl group could be transformed to a nucleophilic species (Scheme **1** (a)). Thus the carbonyl group could attack the electrophiles by so called *umpolung* character. The activation of the carbonyl groups by NHCs is shown in scheme **1** (b) including condensation, 1,4-addition, and transesterification[1]. One of the most studied reactions emplolying NHCs as an organocatalyst is the benzoin condensation and this example will be discussed using polymeric NHCs in Chapter **1**.

Basically a catalyst is not consumed during the process, its separation from the final products is sometimes difficult. To consider the efficient and economic relevance, intense interest has emerged in the development of heterogenization of catalysts.[4] The conventional method for heterogenization is using resin supported system which is the process of attaching the catalyst to insoluble organic or inorganic carriers.[5] However, this method often shows different performances than the original catalyst in homogeneous environment. Thus, a promising method for overcoming such limitations is to incorporate an organocatalyst into a soluble, recovered polymer. Since the polymerization of catalysts has been used as one of heterogenization methods, efforts were directed toward the development of a recyclable polymeric NHC.[6]

The polymeric NHC, known as poly(NHC), has many benefits that overcomes monomeric NHC. Poly(4-vinylimidazolium)s[7] which are the active precursor for poly(NHC) bridge homogeneous and heterogeneous catalysis. That means poly(4-

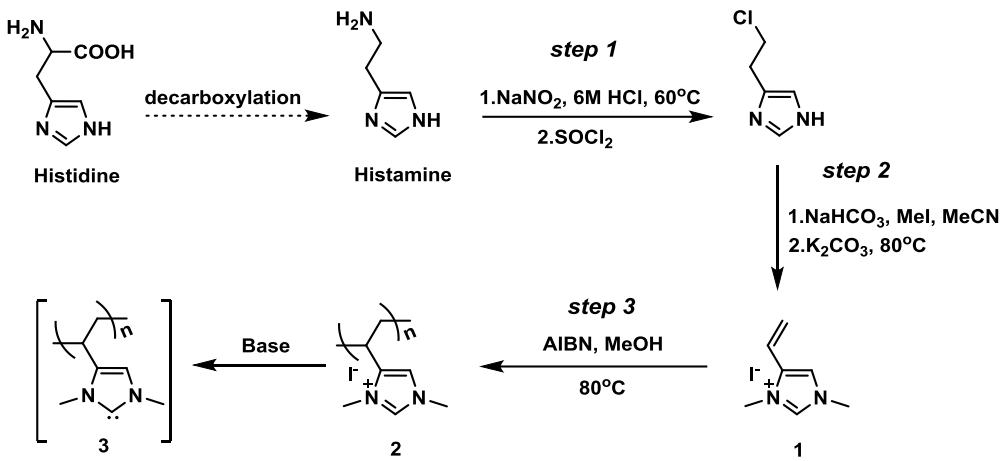
vinylimidazolium)s have both characters, acting as homogeneous catalysis for high activity as well as heterogeneous catalysis for ease of catalyst recovery and recycling. Poly (4-vinylimidazolium)s are well soluble in high polar solvent such as DMF, DMSO or water but insoluble in common organic solvent like acetone, ethyl acetate, methanol. By using the solubility differences, the poly(4-vinylimidazolium)s can be soluble into the solution for homogeneous catalysis and then recovered back to the solid catalyst through pouring the insoluble solvent after the reaction. Therefore, the use of solubility differences, this catalytic system enables both homogeneous and heterogeneous characters. Furthermore, poly(4-vinylimidazolium)s show higher activities because the active centers of a catalyst are distributed over the polymer chain, which helps preventing the loss of activity. Also, the pendent type of catalyst may affect the higher activities.

Comparing to poly(1-vinylimidazolium)s[8] system, poly(4-vinylimidazolium)s have more chance to be diversity and stability. Since 4-vinylimidazolium has two nitrogen which can be binding to substituents, poly(4-vinylimidazolium)s are easy to be tunable. Besides, two substituents could give electrons to the imidazolium ring to enhance the electronic or steric power. Some alkyl or aryl groups were tested to get the insight of reactivities. It is noteworthy that dimethyl substituent, 1,3-dimethyl-4-vinylimidazolium, showed the best performances.

Part I will discuss of poly(4-vinylimidazolium)s as a catalyst for the reaction of benzoin condensation[7a] as well as cycloaddition of carbon dioxide to epoxide[7b]. From now on, the catalyst **1** is representing a monomeric precatalyst as 4-vinylimidazolium, and **2** is indicating the polymeric catalyst as poly(4-vinylimidazolim)s.

Synthesis and characterization of poly(4-vinylimidazolium)s

Poly(1,3-dimethyl-4-vinylimidazolium) iodide is synthesized from histamine. Three steps are needed.



Scheme 2. Synthesis of **2** from histamine

Step 1. Chlorination of histamine

4-(2-Chloroethyl)-1H-imidazole was prepared from histamine. 5 g of histamine was dissolved in 20 mL of water and 12 mL of 6 N HCl solution was added to the reaction mixture. The reaction mixture was heated at 60 °C. 4 g of $NaNO_2$ in 20 mL of water solution was dropped into the solution. The mixture was stirred for 2 h. Then white solid was filtered off and washed with ethanol. The filtrate was removed in vacuo. 6 mL of thionyl chloride was then added to the filtrate and the mixture was gentle refluxed (60 °C) for 30 min. When the reaction mixture turned to the orange color, the rest thionyl chloride was removed under vacuum. The orange colored solid was then recrystallized with ethyl acetate/ acetone. White solid was obtained.

Step 2. Synthesis of monomeric precatalyst (1)

4-(2-Chloroethyl)-1H-imidazole (1.3 g, 10 mmol), sodium bicarbonate (4.2 g, 50 mmol), potassium carbonate (6.9 g, 50 mmol), iodomethane (2.4 mL, 40 mmol) and acetonitrile (60 mL) were added to a Schlenk flask. The reaction mixture was stirred under reflux for 18 h. The reaction mixture was filtered over celite and the solvent was removed in vacuo. Then, the reaction mixture was purified by a flash chromatography on a silica gel column eluting with dichloromethane/methanol (v/v, 4:1).

Step 3. Synthesis of polymeric precatalyst (2)

In a typical experiment, a 10 ml Schlenk tube was flame-dried and charged with 3 mmol of 1, 0.012 mmol of AIBN and 2.4 ml of methanol with a glass septum. The Schlenk tube was subjected to three freeze-evacuate-thaw cycles and placed in a thermostatted oil bath previously maintained at 80 ^{o}C. The polymerization reaction was quenched after 11 h by a sudden cooling with liquid nitrogen. The resulting poly(1,3-dimethyl-43-vinylimidazolium) salt **2** was isolated by precipitation in acetone solution. After drying under vacuum, **2** was obtained as a yellowish powder. Yield: 95 %.

Characterization of Precatalyst 2 by Static Light Scattering (SLS)

Sample preperation and measurement

Absolute MW value was measured by SLS. The solvent, DMF, was filterd by using a 0.2 μm PVDF filter for removing dust before use. The initial concentration of

catalyst solution was 25 mg/25 mL (1 g/L). The solutions of **2** were prepared in a pre-cleaned vial with ultra sonnication for 6 h to get a homogeneous solution. Then the high concentration (1 g/L) was diluted to 0.25, 0.3, 0.35, 0.4, 0.45, 0.5 g/L with adding DMF in pre-cleaned vials. Then, the solutions with various polymer concentrations were filtered again through 0.2 μm PVDF filters and ultra sonicated overnight to stabilize the solutions before SLS measurements. The light scattering measurements were carried out at 14 ^{o}C. Measurements were taken using a DLS-7000 apparatus, a commercial spectrometer from Otsuka electronics. The light source was argon ion laser operated at a power of 75 mW and a wave length of the 488 nm which was focused on the sample cell. The scattered angles were taken from 40 to 130 degree, 10 degree of intervals for each sample. The refractive index increment (dn/dc) was measured on an Otsuka electronics DRM-1021 to calculate the weight average molecular weight for catalyst.

Zimm plot by Static Light Scattering

The second virial coefficient, A2, obtained from the SLS measurement, denotes the degree of the polymer–solvent interaction in the dilute solution. Figure 1 shows the Zimm plot of poly(1,3-dimethyl-4-vinylimidazolium) iodide/DMF solution at 14 ^{o}C. The A2 is about -1.683 x 10^{-1} cm^3 mol g^{-2} at 14.1 ^{o}C. The negative A2 values are still found at the whole range of the measuring temperature in this work. The absolute Mw value was determined by SLS and the value was **2.990 x 10^4**.

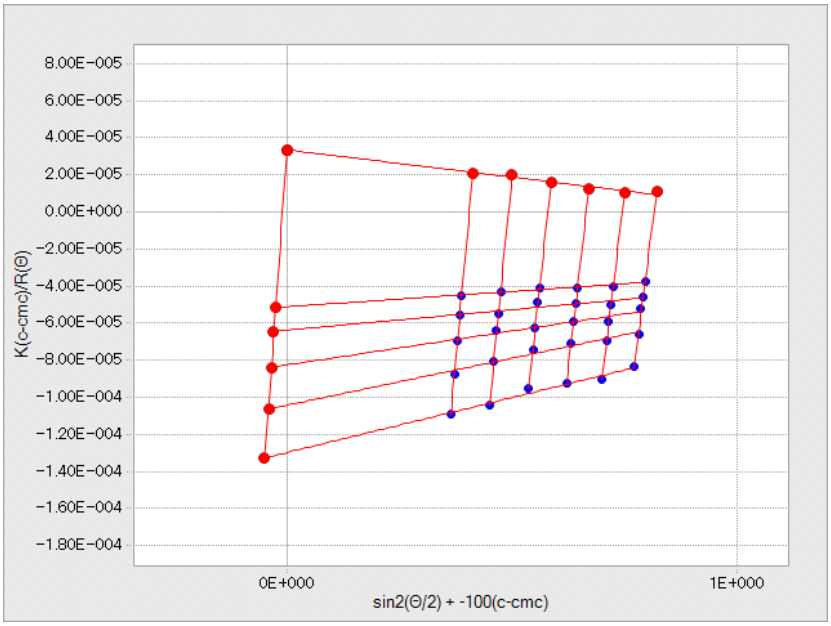


Figure 1. Zimm plot of poly(4-vinylimidazolium) in DMF solution at 14 °C

Table 1. Measurement conditions of SLS

Measurement condition	
dn/dc (mL/g)	0.3403
Solvent refractive index	1.4200
Temperature (°C)	14.1
Ph 1	Open
Ph 2	Slit
ND Filter	10%
Angle (°)	80, 90, 100, 110, 120, 130
Concentration (mg/ml)	0.25, 0.3, 0.35, 0.4, 0.5

Chapter 1.

Poly (4-vinylimidazolium) iodides: a highly recyclable organocatalyst precursor for benzoin condensation reaction

1. Introduction

Organocatalysis related to green chemistry has attracted much attention and significantly progressed in recent years.[9] Imidazoles obtained from heterocycles are widely used as Lewis basic organocatalysts.[10] One of the most studied reactions by organocatalysis is the benzoin condensation reaction which affords α-hydroxyketones (acyloins) via the self-condensation of two aromatic aldehydes.[11] The benzoin condensation reaction is initially carried out under toxic cyanide ion. However, the development of N-Heterocyclic carbene (NHC) enriches mild reaction conditions by its *umpolung* character. Benzoins, α-hydroxyketones, are important building blocks in organic synthesis and found in many biologically active compounds.[12]

Organocatalytic reactions are usually carried out under homogeneous conditions. However, due to the economic and environmental issues, many studies have been focused on reducing waste and reusing materials. In this regard, several studies on the heterogenization of organocatalysts using organic polymers[13] or mesoporous materials[14] have been reported. However, some of them suffered from relatively low yields and poor recyclability, probably because of the lower stability or degradation of the catalysts under basic conditions. In 2011, Cowley reported a self-supported poly(NHC), with *in situ* generated NHCs orthogonally positioned along a main chain.[15] However, the catalytic activity of this catalyst for benzoin condensation was not satisfactory. The recyclability of the catalyst (10 mol%) was investigated only in three successive benzoin condensation reactions (67%, 66%, and 64% yields, respectively). Likewise Taton et al. reported the synthesis of poly(1-vinyl-3-alkylimidazolium)s from 1-vinylimidazolium and their use as a precatalyst in

benzoin condensation reactions.[8a] However, poor recyclability with a lower yield was observed. Therefore, our research was focused on the the development of highly recyclable catalyst for benzoin condensation reaction.

We envisioned that poly(4-vinylimidazolium)s (**2**) would be a very useful polymeric support material and function as a polymerized catalyst.[16] The *in situ* generated poly(NHC)s (**3**) exhibits higher catalytic activity than the corresponding monomeric analog and can be recycled repeatedly without loss in performance in the benzoin condensation reaction. It is noteworthy that the polymeric NHC showed higher activities than those of monomeric catalyst. Herein we report the use of poly(4-vinylimidazolium)s as an organic precatalyst for N-heterocyclic carbene-catalyzed benzoin condensation reaction and the tandem reaction of benzaldehyde and methyl acrylate to afford γ-butyrolactone. As far as we are aware, our study shows the first successfully recyclable catalytic system for benzoin condensation reaction.

2. Result and Discussion

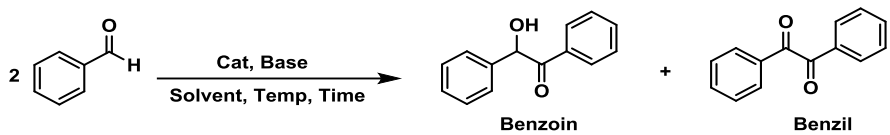
Starting from histamine, 4-vinylimidazolium (**1**) and poly(4-vinylimidazolium)s (**2**) were prepared. With **1** and **2** in hand, their abilities to catalyze the benzoin condensation were investigated (eq 1).

(eq. 1)

First, the reaction conditions were investigated, including the reaction temperature, solvent and base to optimize the yield of benzoin (Table **2**).

The yield of the reaction in the presence of **2** was highly sensitive to the base, reaction solvent, and reaction temperature. In the absence of a base or in the presence of triethylamine (TEA) as the base, no reaction was observed (entries 1 and 3). A particular range of reaction temperature (40-50 ^{o}C) in dimethyl formamide (DMF) maximized the yield of the reaction (entries 5-9). The amount of DBU could be reduced to 0.3 equiv without decreasing the yield (entries 10-11). As shown in Table **2**, benzoin was obtained as the major product with benzil in various yields as the byproduct. The yields and product distributions were also highly dependent on the acidification after ther reaction (entry 11 vs. 12). Since the remaining DBU functioned as a catalyst in the conversion of benzoin to benzil, [17] the acidification of reaction mixture before exposing to air protects the transformation of benzoin to benzil in air. Thus, when the reaction mixture was treated with 4 M HCl in dioxane after the reaction, the best result was achieved (entry 12).[18]

Table 2. Optimization of reaction conditions [a,b]



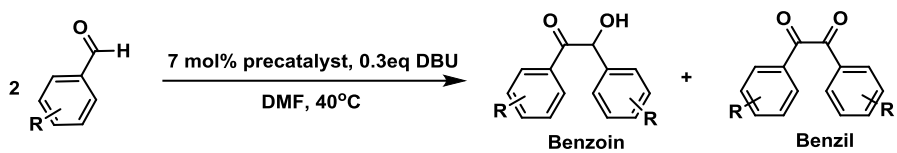
Entry	Base	Solvent	Temp	Yield (%)		
				Benzoin	Benzil	Total
1	none	DMF	40	0	0	0
2	t-BuOK	DMF	60	11	9	20
3	TEA	DMF	60	0	0	0
4	DBU (1 eq)	H2O	60	0	1	1
5	DBU (1 eq)	DMF	60	60	21	81
6	DBU (1 eq)	DMF	80	31	20	51
7	DBU (1 eq)	DMF	50	69	22	91
8	DBU (1 eq)	DMF	40	62	33	95
9	DBU (1 eq)	DMF	r.t	21	21	42
10	DBU (0.5 eq)	DMF	40	74	22	96
11	DBU (0.3 eq)	DMF	40	82	15	97
12[b]	DBU (0.3 eq)	DMF	40	96	1	97
13[c]	DBU (0.3 eq)	DMF	40	62	10	72

[a] Reaction conditions: 1.8 mmol benzaldehyde, 7 mol% catalyst, appropriate equiv of base were reacted in 1 ml solvent were reacted under nitrogen atmosphere. [b]Acidification after reaction. [c] **1** as a catalyst precursor.

The optimum reaction conditions were as follows: 7 mol% **2**, 0.3 equiv DBU, 1 mL DMF, 40 ^{o}C, and 24 h. Moreover, the catalytic activity of **2** was higher than that of **1** (entry 12 *vs*. 13).

Using the optimized reaction conditions, the catalytic activity of **1** and **2** were investigated for diverse functionalized derivatives (Table **3**). Benzoins were obtained as the major products with benzil as the byproduct in various yields (less than 7%). Interestingly, the yields and distributions of the products were highly dependent on the substituent on the benzaldehydes. The yields of benzoin products in the presence of **2** were moderate to excellent (48-96 %). The electronic and steric nature of the substituents did not affect the yield of the benzoins. The total yields of the benzoin and benzil in the presence of **2** were moderate to excellent (52-97 %). As expected, higher yields were observed in the presence of **2** in all the cases than **1**. Strangely, when 4-methoxybenzaldehyde was used as the substrate, a poor yield (< 10%) was obtained. However, when the reaction temperature was raised to 80 ^{o}C, the expected reaction product was obtained in 77% yield and with 21% recovery of the reactant (entry 5). Notably, pyridine-3-carboxaldehyde in the presence of **2** afforded a benzil derivative, 1,2-di(pyridine-3-yl)ethane-1,2-dione, as the only product in 93% yield (by ^{1}H NMR) (data not shown in Table **3**). It has been reported that 2-pyridinecarboxaldehyde is easily oxidized to α-pyridil in methanol at room temperature in air.[19]

Table 3. Benzoin reactions with various benzaldehydes [a]



Entry	R	Yield (%) by **1**			Yield (%) by **2**		
		Benzoin	Benzil	Total	Benzoin	Benzil	Total
1	H	69	3	72	96	1	97
2	m-Br	69	11	80	81	7	88
3	p-Br	40	9	49	48	4	52
4	p-Me	68	5	73	72	3	75
5	p-MeO	75	0	75	77[b]	0	77
6	p-CF_3	40	5	45	71	4	75
7	p-Cl	68	8	76	80	4	84

[a] Isolated yields. [b] Reaction temp. 80 °C

The reusability of **2** was also examined (Fig **2**). The polymer catalyst was recovered by the addition of excess acetone into the reaction mixture. The precipitate was filtered and washed with acetone and dried. Because a small amount of **2** was used as the catalyst, the effect of loss during the separation seemed to be very significant. After seven reaction cycles, 15% of **2** was lost. As shown in Fig **2**, the catalyst was successfully reused without loss of performance over seven cycles.

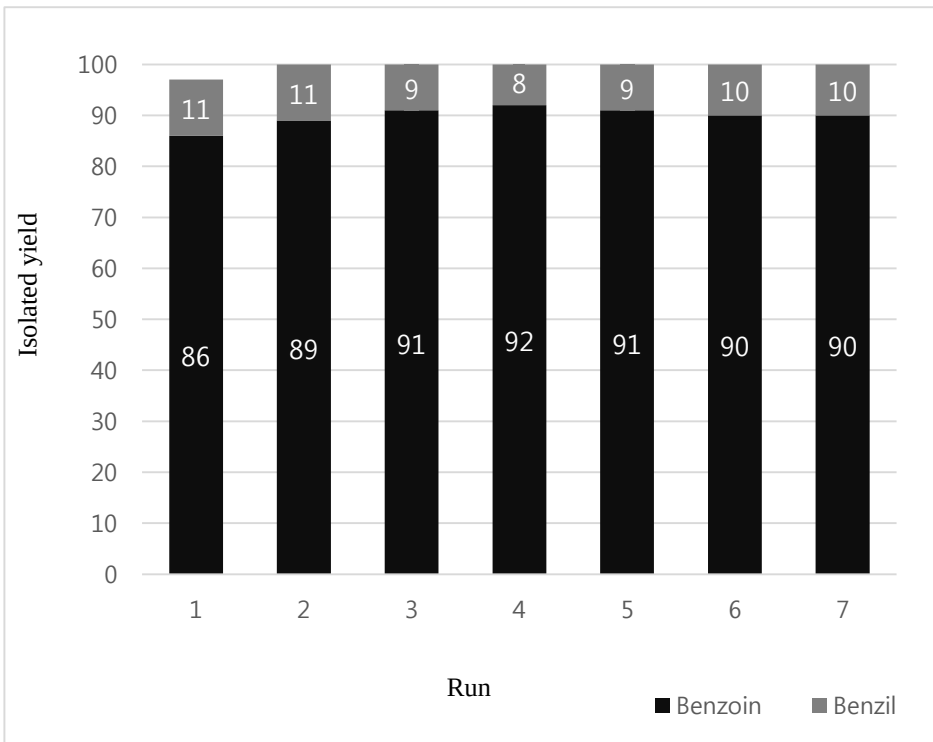
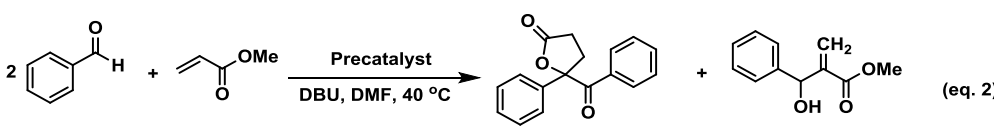


Figure 2. Recycling of polymer catalyst in benzoin condensation reaction

Our excellent result is in contrast to that obtained for poly(1-vinylimidazolium)s.[8a] In that study, poor recyclability with lower yields was observed even after the first and subsequent recycling catalytic reactions and a partial deactivation of poly(1-vinylNHC)s due to the trace impurities was proposed. The deactivation of *in situ* generated poly(1-vinylNHC)s is more likely to occur because of relatively high temperature (80 ^{o}C). However, we expected that the significant difference in the reusability between poly(1-vinylNHC)s and poly(4-vinylNHC)s might arise from the stability of poly(NHC)s under the reaction and workup conditions.

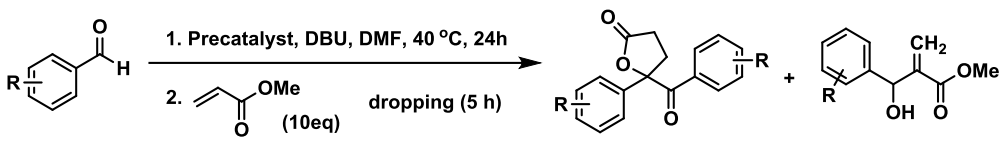
Zhai et al. reported[20] the one-step synthesis of γ-butyrolactones from benzoins/ benzaldehydes and methyl acrylate in the presence of a catalyst generated from the reaction of 1,3-dimethylimidazolium with a base. We also investigated the tandem reaction of benzaldehyde and methyl acrylate catalyzed by **2** in the presence of DBU. After the reaction, γ-butyrolactone was isolated in 78% yield and with a concomitant formation of an allylic alcohol in 6% yield (eq 2).



(eq. 2)

DBU-catalyzed Baylis-Hillman reaction afforded allylic alcohol.[21] However, allylic alcohol was not obtained in the presence of 1,3-dimethylimidazolium and a base (KO^{t}Bu).[20] We investigated the substrate scope of this tandem reaction in the presence of **1** or **2** as the catalyst precursor (Table **4**).

Table 4. Reaction of aromatic aldehydes with methyl acrylate[a,b]



Entry	R	Yield (%) by **1**		Yield (%) by **2**	
		Lactone	Ally alcohol	Lactone	Ally alcohol
1	H	60	8	60	8
2	m-Br	26	6	26	6
3	p-Me	60	trace	60	trace
4	p-Cl	34	trace	34	trace
5	p-MeO	50[c]	trace	50[c]	trace

[a] Reaction conditions: 1.8 mmol benzaldehyde, 7 mol% catalyst, 0.3 equiv. DBU, 1 mL of DMF at 40 °C for 24 h under N_2/18 mmol methyl acrylate for 5 h. [b] Isolated yield. [c] Reaction temp. 80 °C

In the presence of **2** and DBU, the yields of lactones were reasonable to high (44-78%). However, the yields in the presence of **1** and DBU were poor to moderate (26-60%). Thus, precatalyst **2** afforded lactones in higher yields than **1**. Allylic alcohols were obtained in better yields for benzaldehyde and *m*-bromobenzaldehyde than for other aldehydes (trace amounts). When *p*-methoxybenzaldehyde was used, a considerable amount of the reactant was recovered.

Cowley et al. synthesized[15] poly(NHC)s, with a different backbone from our poly(NHC)s, and used in benzoin condensation reaction. They also observed higher catalytic activity of poly(NHC)s than the corresponding monomeric analog. Xie et al. investigated[22] di- and triimidazolium salts as the catalysts for benzoin condensation reaction. In contrast to our results, the catalytic activity of di- and triimidazolium salts was inferior to that of the catalyst with only one imidazolium moiety, probably because of the increase in the steric hindrance by adding of an imidazolium ring. The highly enhanced reactivity of **2** may be attributed to the synergistic effect between the catalytically active sites along the polymer backbone[15,23] or a higher density of active sites. In addition, the active sites linked to the polymer backbone in a pendant fashion may help to increase the reactivity.

In conclusion, we developed a polymer-based organocatalytic system (**2**) that shows high catalytic activity in benzoin condensation reaction and the tandem formation of γ-butyrolactone from benzaldehyde and methyl acrylate. Precatalyst **2** showed higher catalytic activity than monomeric analog (**1**). Moreover, **2** showed higher reusability in the benzoin condensation reaction compared to the polymerized precatalysts obtained from 1-vinylimidazolium. Organocatalytic system **2** synthesized in three steps from commercially available materials, has great potential for practical use and recovery of the polymerized catalysts in benzoin condensation reaction.

3. Experimental Section

General

All solvents were obtained by passing through activated alumina columns of solvent purification systems from Glass Contour. n-Hexanes and ethyl acetate were used without further purification. Reagents were purchased from Sigma-Aldrich, Alfa Aesar, Acros, TCI and were used as received. Reactions were carried out in a flame -dried glassware equipped with a stirring bar and capped with a rubber septum under N_2, unless otherwise indicated. Elevated temperatures were maintained in thermostat-controlled oil baths. The TLC plate was carried out on 0.25 mm E. Merck silica gel plates (60F-254) visualized by UV-light (254 nm) and treatment with acidic *p*-anisaldehyde and $KMnO_4$ stain followed by gentle heating. Workup procedures were done in air. Flash chromatography was carried out on Merck 60 silica gel (230 – 400 mesh). ^1H and ^{13}C NMR spectra were recorded with Bruker (300 MHz) and Varian spectrometer (400 MHz) spectrometer. ^1H NMR spectra were referenced to residual TMS (0 ppm) except D_2O (solvent reference, 4.79 ppm) and reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, dd = doublet of doublets, ddd = doublet of doublet of doublets, ddt = doublet of doublet of triplets, dt = doublets of triplets, br s = broad singlet, m = multiplet). Chemical shifts of the ^{13}C NMR spectra were measured relative to $CDCl_3$ (77.16 ppm). Mass spectral data were obtained from the Korea Basic Science Institute (Daegu) on a Jeol JMS 700 high resolution mass spectrometer. Static light scattering (SLS) measurements were measured by Dynamic Light Scattering Spectrophotometer (DLS-7000) at National Instrumentation Center for Environmental Management (NICEM), College of Agriculture and Life Sciences,

Seoul National University, Korea. Azobisbutyronitrile (AIBN) was purchased and recrystallized from methanol before use.

General procedure for the synthesis of benzoins and benzils from benzaldehydes

Reactions were performed in a schlenk tube equipped with a stirring bar and a rubber septum and the followings were placed in the tube in order: 7 mol% of catalyst (31 mg, 0.13 mmol), 1.8 mmol of benzaldehyde, 0.3 eq of DBU (81 μL, 0.54 mmol) and 1 mL of DMF. After the mixture was stirred at 40 ^{o}C for 24 h, 0.45 mL of 4 M HCl in dioxane solution was added to the reaction mixture. The resulting solution was stirred for an additional 1 h. Addition of excess acetone to the reaction mixture led to precipitae poly(NHC)s. After filtration, the filtrate was concentrated under reduced pressure. Purification by a flash chromatography on silica gel column eluting with *n*-hexane and ethyl acetate affords benzoin and benzil as products. In a case of pyridine-3-carboxaldehyde, purification was done by using an alumina column eluting with dichloromethane and methanol.

Procedure for the Synthesis of γ-Butyrolactones from Benzaldehyde and Methyl Acrylate.

Reactions were performed in a flame-dried 8 mL Schlenk tube equipped with a stirring bar and a rubber septum. The flask was charged with 7 mol% of catalyst (31 mg, 0.13 mmol), 1.8 mmol of benzaldehyde, 30 mol% of DBU (81 μL, 0.54 mmol) and 1 mL of DMF. The mixture was stirred at 40 ^{o}C for 24 h. Then, methyl acrylate (1.63 ml, 18 mmol) was added, and the reaction mixture was stirred for an additional

5 h. Water was added to the reaction mixture and products were extracted with ethyl acetate 5 times. The organic layer was dried over anhydrous $MgSO_4$ and concentrated under reduced pressure. Purification by flash chromatography on a silica gel column eluting with *n*-hexane and ethyl acetate afforded γ-butyrolactones and allylic alcohols, respectively.

Recycling experiment

A Schlenk tube was charged with 7 mol% of catalyst **2** (31 mg, 0.126 mmol), 0.3 equiv of DBU (81 μL, 0.54 mmol), benzaldehyde (0.191 g, 1.8 mmol), and 1 mL of DMF. After the mixture was stirred for 24 h at 40 °C, poly(4-vinylNHC)s were successfully recovered by precipitation from the reaction mixture by addition of acetone. The filtrate was immediately introduced to the acid solution to avoid formation of benzil. 4 M HCl in dioxane solution was used for the acid solution. The solvent was evaporated from the filtrate, and the residue was purified by a flash column chromatograpy. The recovered poly(4-vinylNHC)s were reused for the next run of benzoin condensation reaction. The catalytic performance of poly(4-vinylNHC)s were well maintained during the seven times of the catalyst reuse, leading to benzoin and benzil products in a range of 97-100% isolated yields.

Characterization of products

Benzoins

Benzoin: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 – 7.88 (m, 2 H), 7.51 (t, *J* = 7.4 Hz, 1 H), 7.39 (t, *J* = 7.7 Hz, 2 H), 7.34 – 7.23 (m, 5 H), 5.95 (d, *J* = 6.1 Hz, 1 H), 4.55 (d, *J* = 6.1 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.0, 139.1, 134.0, 133.6, 129.2(2), 128.7, 128.6, 127.8, 76.3 ppm. HRMS (EI) calc. for [$C_{14}H_{12}O_2$]: 212.0837, found: 212.0835. m.p.: 131 ºC, white solid.

p-Methyl benzoin: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.72 (d, *J* = 8.2 Hz, 2 H), 7.12 (d, *J* = 8.0 Hz, 2 H), 7.06 (d, *J* = 8.1 Hz, 2 H), 7.00 (d, *J* = 7.9 Hz, 2 H), 5.80 (d, *J* = 5.5 Hz, 1 H), 4.50 (d, *J* = 5.9 Hz, 1 H), 2.22 (s, 3 H), 2.16 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 198.5, 144.9, 138.3, 136.4, 130.9, 129.8, 129.3(2), 127.6, 75.8, 21.7, 21.1 ppm HRMS (EI) calc. for [$C_{16}H_{16}O_2$]: 240.1150, found: 240.1151. m.p.: 86 ºC, white solid.

p-Methoxy benzoin: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.89 (d, *J* = 8.9 Hz, 2 H), 7.24 (d, *J* = 8.7 Hz, 2 H), 6.83 (dd, *J* = 8.8, 2.9 Hz, 4 H), 5.85 (d, *J* = 5.4 Hz, 1 H), 4.61 (d, *J* = 5.7 Hz, 1 H), 3.78 (s, 3 H), 3.72 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.4, 164.1, 159.7, 131.9, 131.6, 129.1, 126.4, 114.6, 114.0, 75.3, 55.6, 55.3 ppm. HRMS (EI) calc. for [$C_{16}H_{16}O_4$]: 272.1049, found: 272.1049. m.p.: 108 ºC, white solid.

p-Chloro benzoin: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.82 (d, *J* = 8.4 Hz, 2 H), 7.37 (d, *J* = 8.4 Hz, 2 H), 7.27 (q, *J* = 8.5 Hz, 4 H), 5.88 (s, 1 H), 4.53 (bs, 1 H) ppm. . ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.4, 140.6, 137.2, 134.7, 131.5, 130.4, 129.4, 129.2, 129.1, 75.5 ppm. HRMS (EI) calc. for [$C_{14}H_{10}Cl_2O_2$]: 280.0058, found: 280.0057. m.p.: 87 ºC, white solid.

p-Trifluoromethyl benzoin: ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.00 (d, *J* = 8.2 Hz, 2 H), 7.69 (d, *J* = 8.3 Hz, 2 H), 7.60 (d, *J* = 8.1 Hz, 2 H), 7.45 (d, *J* = 8.1 Hz, 2 H), 6.02 (d, *J* = 5.9 Hz, 1 H), 4.51 (d, *J* = 5.9 Hz, 1 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ 197.8, 142.6, 136.0, 135.7, 135.3, 131.4, 131.0, 129.5, 128.2, 126.4(q, J = 3.8 Hz), 126.1(q, J = 3.6 Hz), 76.1 ppm. HRMS (EI) calc. for [$C_{16}H_{10}F_6O_2$]: 348.0585, found: 348.0583. m.p.: 93 °C, white solid.

m-Bromo benzoin: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.06 (s, 1 H), 7.77 (d, *J* = 7.4 Hz, 1 H), 7.65 (d, *J* = 7.5 Hz, 1 H), 7.53 – 7.37 (m, 2 H), 7.33 – 7.17 (m, 3 H), 5.86 (s, 1 H), 4.45 (bs, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.2, 140.4, 136.9, 134.9, 131.9(2), 130.7, 130.6, 130.3, 127.5, 126.3, 123.2, 123.1, 75.5 ppm. HRMS (EI) calc. for [$C_{14}H_{10}Br_2O_2$]: 367.9048, found: 367.9044. m.p.: 57 °C, yellow solid.

p-Bromo benzoin: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.74 (d, *J* = 8.4 Hz, 2 H), 7.56 (d, *J* = 8.6 Hz, 2 H), 7.46 (d, *J* = 8.8 Hz, 2 H), 7.18 (d, *J* = 8.1 Hz, 2 H), 5.86 (d, *J* = 6.0 Hz, 1 H), 4.46 (d, *J* = 6.3 Hz, 1 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ 197.7, 137.7, 132.5, 132.3, 132.0, 130.6, 129.6, 129.4, 123.1, 75.6 ppm. HRMS (EI) calc. for [$C_{14}H_8Br_2O_2$]: 367.9048, found: 367.9049. m.p.: 92 °C, white solid.

Benzils

Benzil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.98 (d, *J* = 7.6 Hz, 4 H), 7.67 (t, *J* = 7.4 Hz, 2H), 7.52 (t, *J* = 7.7 Hz, 4 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ 194.7, 135.0, 133.1, 130.0, 129.1 ppm. HRMS (EI) calc. for [$C_{14}H_{10}O_2$]: 210.0681, found: 210.0684. m.p.: 92 °C, yellow solid.

p-methyl benzil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.86 (d, *J* = 8.2 Hz, 4 H), 7.30 (d, *J* = 8.0 Hz, 4 H), 2.43 (s, 6H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 194.6, 146.2, 130.8,

130.1, 129.8, 22.0 ppm. HRMS (EI) calc. for [$C_{16}H_{14}O_2$]: 238.0994, found: 238.0996. m.p.: 94 °C, yellow solid.

p-Chloro benzil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.92 (d, *J* = 8.6 Hz, 4 H), 7.50 (d, *J* = 8.6 Hz, 4 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 192.5, 141.9, 131.4, 131.2, 129.6 ppm. HRMS (EI) calc. for [$C_{14}H_8Cl_2O_2$]: 277.9901, found: 277.9901. m.p.: 195 °C, yellow solid.

p-Trifluoromethyl benzil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.12 (d, *J* = 8.1 Hz, 4 H), 7.81 (d, *J* = 8.3 Hz, 4 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ 192.0, 136.6, 136.1, 135.3, 130.5, 126.3(q, J = 3.7 Hz) ppm. HRMS (EI) calc. for [$C_{16}H_8F_6O_2$]: 346.0428, found: 346.0431. m.p.: 132 °C, white solid.

m-Bromo benzil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.13 (t, *J* = 1.8 Hz, 2 H), 7.89 (ddd, *J* = 7.8, 1.6, 1.1 Hz, 2 H), 7.81 (ddd, *J* = 8.0, 2.0, 1.1 Hz, 2 H), 7.42 (dd, *J* = 11.7, 4.1 Hz, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 192.0, 138.1, 134.4, 132.7, 130.7, 128.7, 123.5ppm. HRMS (EI) [$C_{14}H_8Br_2O_2$]: 365.8891, found: 365.8894. m.p.: 122 °C, yellow solid.

p-Bromo benzil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.84 (d, *J* = 8.5 Hz, 4 H), 7.67 (d, *J* = 8.5 Hz, 4 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ 192.6, 132.6, 131.6, 131.4, 130.9 ppm. HRMS (EI) [$C_{14}H_8Br_2O_2$]:365.8891, found:365.8889. m.p.: 220 °C, yellow solid.

1,2-Di(pyridin-3-yl)ethane-1,2-dione:^{1}H NMR (400 MHz, $CDCl_3$) δ 9.20 – 9.15 (m, 2 H), 8.87 (dd, *J* = 4.8, 1.7 Hz, 2 H), 8.32 (dt, *J* = 8.0, 2.0 Hz, 2 H), 7.49 (dd, *J* = 8.0, 4.9 Hz, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.0, 155.2, 151.5, 137.1, 128.3, 124.0 ppm. HRMS (EI) [$C_{12}H_8N_2O_2$]:212.0586, found:212.0587.

Lactones

5-Benzoyl-5-phenyltetrahydro-2(*3H*)- furanone: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.98 – 7.92 (m, 2 H), 7.47 (m, 3 H), 7.42 – 7.36 (m, 2 H), 7.33 (ddd, *J* = 7.5, 4.3, 1.9 Hz, 3 H), 3.42 (ddd, *J* = 13.0, 8.2, 7.1 Hz, 1 H), 2.63 – 2.52 (m, 2 H), 2.33 (dt, *J* = 13.0, 8.4 Hz, 1 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ 195.3, 175.5, 139.4, 133.6, 133.5, 130.8, 129.3, 128.6, 128.3, 123.8, 92.1, 34.4, 29.0 ppm. HRMS (EI) calc. for [$C_{17}H_{14}O_3$]: 266.0943, found: 266.0940, colorless oil.

5-(4-Methylbenzoyl)-5-(4-methylphenyl)-tetrahydro-2(3*H*)-furanone: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 – 7.84 (m, 2 H), 7.37 – 7.32 (m, 2 H), 7.18 (d, *J* = 7.9 Hz, 2 H), 7.14 – 7.10 (m, 2 H), 3.39 (m, 1 H), 2.59 – 2.51 (m, 2 H), 2.34 – 2.25 (m, 7 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ 194.9, 175.8, 144.4, 138.4, 136.7, 131.0, 131.0, 129.9, 129.0, 123.7, 92.3, 34.4, 28.1, 21.7, 21.1 ppm. HRMS (EI) calc. for [$C_{19}H_{18}O_5$]: 294.1256, found: 294.1256, colorless oil.

5-(4-Methoxybenzoyl)-5-(4-methoxyphenyl)-tetrahydro-2(3*H*)-furanone: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.00 – 7.94 (m, 2 H), 7.40 – 7.34 (m, 2 H), 6.92 – 6.87 (m, 2 H), 6.83 – 6.78 (m, 2 H), 3.79 (s, 3 H), 3.77 (s, 3 H), 3.38 (m, 1 H), 2.58 – 2.51 (m, 2 H), 2.29 (dt, *J* = 13.0, 8.3 Hz, 1 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ 193.7, 175.8, 163.6, 159.6, 133.2, 131.6, 126.3, 125.1, 114.5, 113.5, 92.0, 55.4, 55.2, 34.3, 28.0 ppm. HRMS (EI) calc. for [$C_{19}H_{18}O_5$]: 326.1154, found: 326.1154, pale-yellow oil.

5-(4-Chlorobenzoyl)-5-(4-chlorophenyl)-tetrahydro-2(3*H*)-furanone: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 – 7.86 (m, 2 H), 7.38 (s, 4 H), 7.34 – 7.30 (m, 2 H), 3.42 (ddd, *J* = 13.2, 8.3, 6.8 Hz, 1 H), 2.62 – 2.54 (m, 2 H), 2.28 (dd, *J* = 8.6, 4.5 Hz, 1 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ 193.7, 175.0, 140.3, 137.7, 134.9, 132.1, 131.6, 129.6,

128.8, 125.2, 91.5, 34.2, 27.9 ppm. HRMS (FAB,[M+H]) calc. for [$C_{17}H_{13}Cl_2O_3$]: 335.0242, found: 335.0243, colorless oil.

5-(3-Bromobenzoyl)-5-(3-bromophenyl)-tetrahydro-2(3*H*)-furanone: ^{1}H NMR (400 MHz, $CDCl_3$)) δ 8.08 (t, *J* = 1.8 Hz, 1 H), 7.85 (m, 1 H), 7.62 (m, 2 H), 7.48 (m, 1 H), 7.38 (m, 1 H), 7.31 – 7.19 (m, 2 H), 3.46 – 3.38 (m, 1 H), 2.61 – 2.55 (m, 2 H), 2.33 – 2.27 (m, 1 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ 193.6, 174.9, 141.3, 136.7, 135.0, 133.4, 132.1, 131.1, 130.0, 129.5, 126.9, 123.8, 122.8, 122.4, 91.2, 34.3, 27.9 ppm. HRMS (EI) calc. for [$C_{17}H_{12}Br_2O_3$]: 421.9153, found: 421.9156, colorless oil.

Chapter 2.

Poly (4-vinylimidazolium)s/ Diazabicyclo[5.4.0]undec-7-ene/ Zinc(II) Bromide-Catalyzed Cycloaddition of Carbon Dioxide to Epoxides

1. Introduction

Carbon dioxide (CO_2) has been attracting much attention as it is considered to be a major cause of climate change, because of its greenhouse effect.[24] In order to reduce the continuous accumulation of CO_2 in the atmosphere, the scientific and industrial initiatives have been focused on the chemical conversion of CO_2 to the valuable chemicals.[25] CO_2 is one of the useful C1 source that has an abundant, inexpensive, non-toxic, and promising renewable resource. However, the chemistry of CO_2 is limited because of its high stability and therefore low reactivity. Thus, synthetic utilizations of CO_2 as a carbon sourse are currently generating great challenges of scientific community.[26]

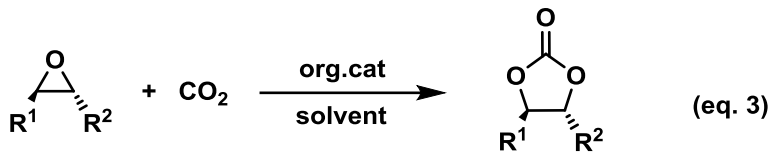
One of the potentially useful ways of reducing CO_2 is its reaction with epoxides to form cyclic carbonates.[27] This reaction has been tremendous potential because cyclic carbonates are widely used as the precursors of polycarbonates and other polymers, excellent aprotic polar solvents, electrolytes in rechargeable batteries, and intermediates in the production of pharmaceuticals and fine chemicals.[28] Therefore, a variety of diverse homogeneous and heterogeneous catalyst systems[29] have been developed for catalyzing the reactions of CO_2 with epoxides. For examples, Ding *et al* reported the use of 1-vinyl- and 1,3-divinylimidazole-based cross-linked polymers as the catalyst in the carboxylation of epoxides with CO_2 has been reported.[30] The use of poly[1,3-bis(4-vinylbenzyl)imidazolium]Cl-based cross-linked polymers as the catalyst in the cycloaddition has also been reported.[31] Moreover, Kelij and co-workers prepared iron(III) amine triphenolate complex to catalyze the cycloaddition of carbon dioxide to a range of terminal epoxides under mild conditions.[32] However,

most of them suffer from low catalytic activity, needs of transition metal, high CO_2 pressure, water or air sensitivity of catalyst, and harsh reaction conditions.

Therefore, the development of more efficient, readily available, and low-cost catalyst and mild protocol is highly desired. In this regard, we have demonstrated that poly(4-vinylimidazolium)s (**2**) derived from self-immobilization of 4-vinylimidazoliums (**1**) acted as a precatalyst in the carboxylation of epoxides with CO_2. We found that combining of polymeric catalyst (**2**) with base and Lewis acid system showed highly efficient for the transformation of cyclic carbonate. Herein we report a very active, stable, recyclable and cost-effective organic precatalyst, poly(4-vinylimidazolium)s (**2**), for the carboxylation of epoxides with CO_2 under mild condition. This protocol provides various substrate scope including terminal epoxides as well as internal epoxides with high functional group tolerances.

2. Results and Discussion

The abilities of **1** and **2** to catalyze the carboxylation of epoxides with CO_2 in the presence of a base were examined (eq 3).



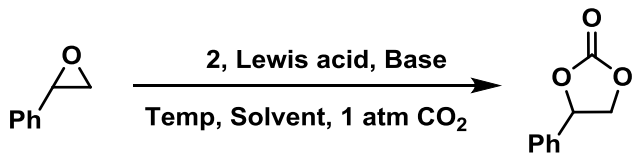
(eq. 3)

First, the reaction conditions were optimized, including the CO_2 pressure, a reaction temperature, a reaction time, a solvent, a base, and the catalyst amount to optimize the yield of a cyclic carbonate (Table **5**). Initially, study was performed under the reaction conditions (2 mol% catalyst, ZnI_2 as the Lewis acid, K_2CO_3 as the base, DMSO as the solvent, at 80 ^oC reaction temperature, and 24 h of reaction time) adopted from the previous work[33] on the NHC-catalyzed carboxylation of epoxides. The coupling of styrene oxide (SO) with CO_2 to afford styrene carbonate (SC) was chosen as the model reaction. When the reaction was carried out under the adopted reaction conditions, the SC yield was 86% (Table 5, entry 1). Changing the solvent to DMF afforded a slightly higher SC yield (entry 2: 88% yield). When diazabicyclo[5.4.0]undec-7-ene (DBU) was used instead of K_2CO_3 in DMF, SC was obtained quantitatively (entries 3 and 4). When the amount of catalyst **2** was reduced to 1 mol%, the yield was still high (entry 5, 90% yield).

Thus, in the presence of 1 mol% of **2**, the effect of metal ions, such as ZnX_2 (X = Cl, Br, and I), $CrCl_3$, LiI, and $FeCl_3$, on the reaction was also examined (entries 5-10). The SC yield was greatly affected by the different metal ions. Among them, the use

of $ZnBr_2$ afforded the best result (entry 6, 94% yield), because of its strong Lewis acidity. The reactivity of different anions in the zinc salts decreased in the following order: $Br^- > I^- > Cl^-$. The different reactivity may be due to the different electrophilicity of Zn depending upon the anion.[34] The effect of the reaction temperature on the product yield was also examined (entries 6, 11, and 12). In the lower temperature range, the yield increased with the increasing temperature (entry 6 *vs* 11); however, this trend was not observed at higher temperatures. The yield decreased to 87 % at 100 ^oC (entry 6 *vs* 12). The reaction proceeded well with 1 mol% of catalyst at 80 ^oC. When the reaction time was reduced to 10 h, the excellent yield maintained (entry 13, 94 % yield). The necessity of a combination of **2**, DBU, and a Lewis acid in the reaction was confirmed by the observation that in the presence of **2**, DBU, or $ZnBr_2$ a negligible reaction was observed (entries 14-16).

Table 5. Screening the reaction conditions[a]



Entry	**2** (mol%)	Solvent	Base (mol%)	Lewis acid	Yield (%)[b]
1	2	DMSO	K_2CO_3 (2)	ZnI_2	86
2	2	DMF	K_2CO_3 (2)	ZnI_2	88
3	2	DMF	DBU (2)	ZnI_2	95
4	2	DMF	DBU (4)	ZnI_2	99
5	1	DMF	DBU (2)	ZnI_2	90
6	1	DMF	DBU (2)	$ZnBr_2$	94
7	1	DMF	DBU (2)	$ZnCl_2$	76
8	1	DMF	DBU (2)	$CrCl_3$	72
9	1	DMF	DBU (2)	LiI	77
10	1	DMF	DBU (2)	$FeCl_3$	77
11[c]	1	DMF	DBU (2)	$ZnBr_2$	50
12[d]	1	DMF	DBU (2)	$ZnBr_2$	87
13[e]	1	DMF	DBU (2)	$ZnBr_2$	94
14	1	DMF	-	-	4
15	-	DMF	DBU (2)	-	N.R
16	-	DMF	-	$ZnBr_2$	11

[a] Reaction conditions: SO (5 mmol), **2**, Lewis acid (the same equiv of **2**), solvent (3 mL), base, and CO_2 (1 atm) at 80 ^oC for 24 h. [b] Isolated yield. [c] Reaction was performed at 60 ^oC. [d] Reaction was performed at 100 ^oC. [e] Reaction time: 10 h.

Thus, the optimum reaction conditions were established as follows: 1 mol% catalyst, 2 mol% DBU, and 1 mol% $ZnBr_2$ in DMF at 80 ^oC under 1 atm CO_2 for 10 h. Under the optimized reaction conditions, the maximum turnover number was 320 (see the experimental section). When **1** was used as the precatalyst under the optimized reaction conditions, SC was obtained in 88% yield. The experiments were also carried out to examine the recyclability of the catalyst using SO as the substrate. The amount of **2** was too small to confirm the recycling test; therefore, twice the amounts of **2**, $ZnBr_2$, and DBU than those used during optimization were used. After performing the reaction in DMF, excess MeOH was added to the reaction mixture to precipitate the polymer catalyst. The recovered polymer catalyst was dried and reused for the next run. The SC yields for the eight consecutive runs were 99%, 98%, 91%, 97%, 97%, 94%, 94%, and 91%. Considering the weight loss in the catalyst purification process, no considerable decrease in the SC yield was observed (fig **3**).

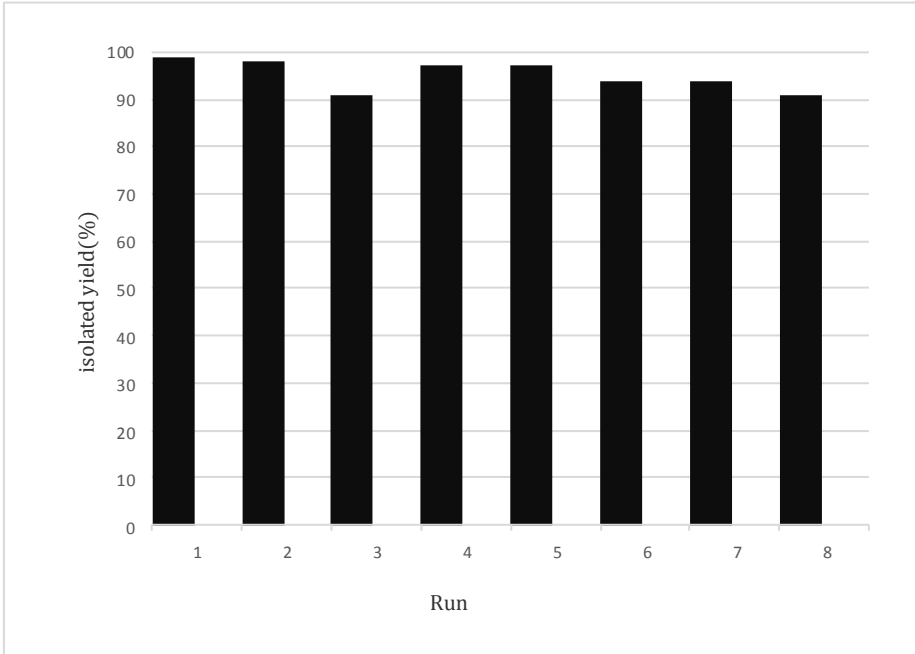
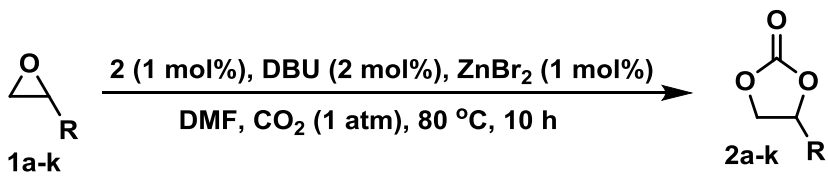
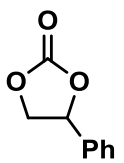


Figure 3. Recycling of poly(NHC-Zn) complex in the cycloaddition of CO_2 to SC.

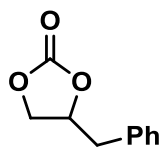
To show the catalytic activity of **3** (**3** = poly(NHC)s; NHC = 1,3-dimethyl-4-vinylimidazol-2-ylidene), the coupling reactions of CO_2 to various substituted epoxides were also conducted at 80 ^oC and 1 atm CO_2 (Table **6**). To our delight, many functional groups, including a chloro, vinyl, ether, and hydroxy groups were well tolerated in the reactions. Thus, all the epoxides except propylene oxide (**1h**) could be transformed to the corresponding carbonates in almost quantitative yields. In the case of propylene oxide, a slightly low yield (56%) was observed because of its low boiling point (33^oC).

Table 6. Cycloaddition of CO_2 with various terminal epoxides [a]

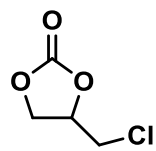




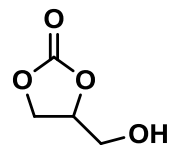
2a, 94 %



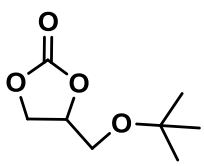
2b, 92 %



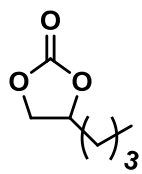
2c, 98 %



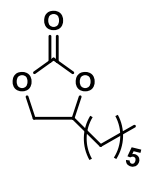
2d, 94 %



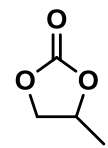
2e, 98 %



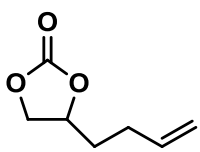
2f, 98 %



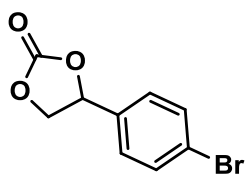
2g, 99 %



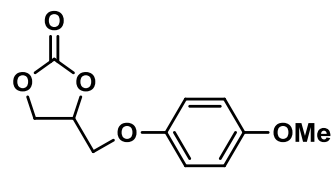
2h, 56 %



2i, 93 %



2j, 93 %



2k, 89 %

[a] 1 mol% of **2**, epoxide (5 mmol), $ZnBr_2$ (1 mol%), DBU (2 mol%), CO_2 (1 atm), 80 ^oC, 10 h, Isolated yields.

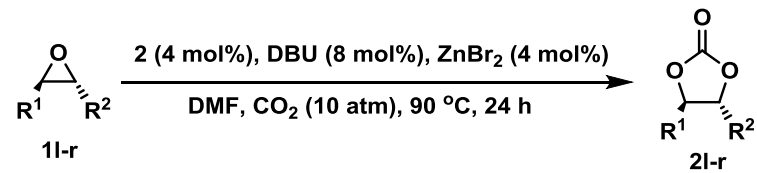
Owing to the steric hindrance and electronic effect, 1,1-disubstituted and internal disubstituted epoxides are often considered to be more challenging substrates for fabricating the cyclic organic carbonates.[35] A series of these substrates (Table **7**) were investigated using the catalyst system. The amounts of **2**, $ZnBr_2$, and DBU were used four times more than those used for the cycloaddition of CO_2 with terminal epoxides. As expected, higher pressures and temperatures were needed to convert the substrates to the corresponding organic carbonates; e.g., the cycloaddition of 1,1-dimethyloxirane(**1l**) with CO_2 at 90 ^oC and 1 atm of CO_2 was unsuccessful. However, under 5 atm of CO_2 pressure, 1,1-dimethyloxirane was converted into 4,4-dimethyl-1,3-dioxolan-2-one in 46% yield after 24 h of reaction time. When the CO_2 pressure was increased to 7 atm and 10 atm, the yields of 4,4-dimethyl-1,3-dioxolan-2-one increased to 53 % and 83 % yields, respectively. Thus, the reactions of other substrates with CO_2 were carried out at 90 ^oC under 10 atm of CO_2. When the CO_2 pressure was increased, most of the substrates afforded the corresponding cyclic carbonates in 68-87% yields. In the case of stilbene oxide (entry 5), a relatively low yield (35%) was observed after 24 h of reaction time. The yield increased to 55% when the reaction time increased to 48 h. Moreover, ethyl 2-oxo-5-phenyl-1,3-dioxalane-4-carboxylate (entry 6) was found to be a good substrate.[36]

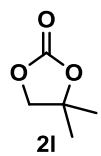
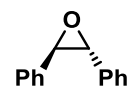
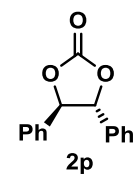
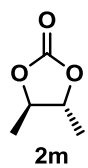
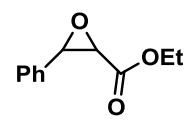
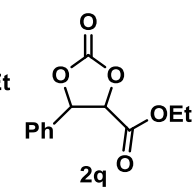
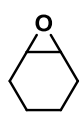
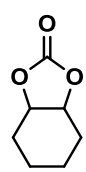
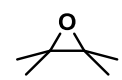
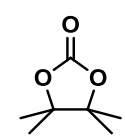
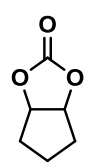
However, in the case of 2,2,3,3-tetramethyloxirane(**1r**), no reaction was observed under the reaction conditions (90 ^oC, 10 atm CO_2, 24 h). When the reaction time was prolonged to 72 h, no reaction was observed.

The internal epoxides provided an opportunity to study the stereochemistry of cyclic carbonate synthesis. According to their ^1H and ^{13}C NMR spectra of them, cyclic

carbonates, (±)-*trans*-4,5-dimethyl-1,3-dioxolan-2-one(**2m**) and (±)-*trans*-4,5-diphenyl-1,3-dioxolan-2-one(**2p**), had the same stereochemistry as that of the starting epoxides used. Thus, the disubstituted epoxides were found to react with retention of configuration.

Table 7. Cycloaddition of CO_2 with various internal epoxides [a]

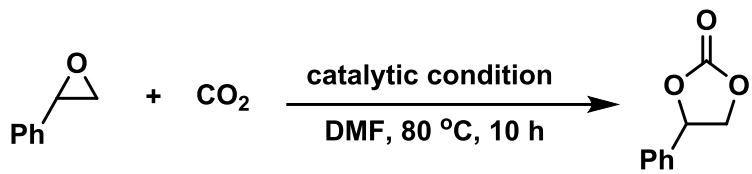


Entry	Substrate	Product	Yield (%)[b]	Entry	Substrate	Product	Yield (%)[b]
1		 2l	83	5[c]		 2p	55
2		 2m	81	6		 2q	68
3		 2n	80	7		 2r	N.R.
4		 2o	87				

[a] The catalyst (4 mol%), $ZnBr_2$ (4 mol%), DBU (8 mol%), expoxide (5 mmol), DMF (4 mL), CO_2 (10 atm), 90 °C, 24 h. [b] Isolated yields. [c] 48 h

To better understand the reaction mechanism, various reaction conditions were tested (Table **8**). The reaction of SO in the presence of $ZnBr_2$ alone afforded SC in 11% yield (entry 1). The same reaction in the presence of $ZnBr_2$ and DBU[37] afforded SC in 43% isolated yield (entry 2). We expected that the reaction of **2** with DBU would afford **3**; however, SC was obtained in 8% yield (entry 3). This observation suggested that **3** would not be generated *in situ*. The rapid CO_2 fixation by DBU and the coupling of aziridine to CO_2 in the presence of DBU have been well documented.[38] However, DBU by itself did not catalyze the reaction (entry 4). The use of imidazolium-based polymeric ionic liquids as catalyst in the reaction of the coupling of CO_2 with epoxides has been reported.[31,39] Thus, the reaction of SO with CO_2 in the presence of **2** and $ZnBr_2$ was examined; and SC was obtained in 45% yield (entry 5). The NHC-CO_2 adduct has been reported to be a potent organocatalyst at high temperatures and high pressures (100-120 °C and 20–100 atm of CO_2 and).[31,39a,40] Thus, **3**-CO_2 adduct was prepared and used as the catalyst. However, no reaction was observed in the presence of **3**-CO_2 adduct (entry 6). Furthermore, the IR spectrum of the recovered poly(NHC)-CO_2 adduct showed that almost all of the CO_2 was lost during the reaction. Thus, the poly(NHC)-CO_2 adduct itself did not play an important role in the catalytic reaction. Interestingly, when the same reaction was carried out in the presence of **3**-CO_2 adduct and $ZnBr_2$ (entry 7), SC was obtained in 33% yield. Thus, the presence of both $ZnBr_2$ and DBU is necessary for achieving good results as similar to those obtained with other Lewis acid and Lewis base co-catalyzed coupling reactions of CO_2 with epoxides.[27,41] Furthermore, the best result was obtained when the reaction was carried out in the presence of **2**, DBU, and $ZnBr_2$ (**2**-DBU-$ZnBr_2$ catalyst system (entry 8, 94% yield).

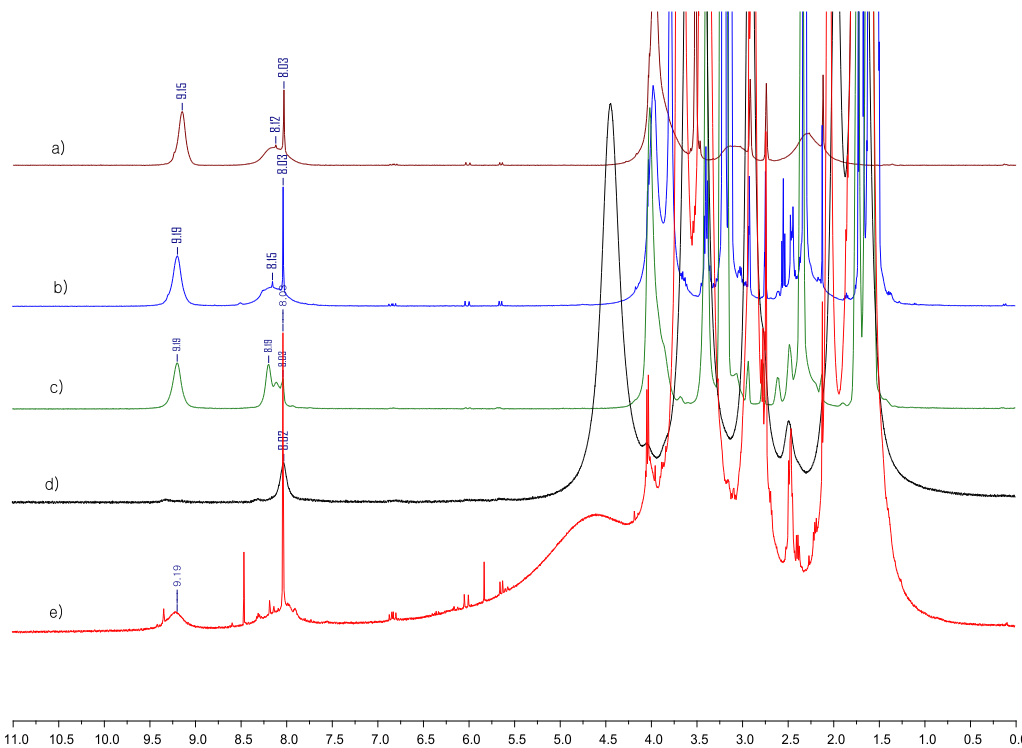
Table 8. Cycloaddition under various reaction conditions [a]



Entry	**2** (mol%)	**3**-CO_2 (mol%)	DBU (mol%)	$ZnBr_2$ (mol%)	Yield (%)
1	0	0	0	1	11
2	0	0	2	1	43
3	1	0	2	0	8
4	0	0	2	0	N.R
5	1	0	0	1	45
6	0	1	0	0	N.R
7	0	1	0	1	33
8	1	0	2	1	94

[a] SO (5 mmol), DMF (3 mL), CO_2 (1 atm), 80 °C, 10 h.

The ^{1}H NMR spectra of **2**, **2**/DBU, and **2**/DBU/$ZnBr_2$ in DMF-d_7 were taken at room temperature and 80 ^{o}C (Fig **4**), the imidazolium C-H peak of **2** appeared at δ 9.15 ppm and was observed in the presence of DBU even at 80 ^{o}C. However, in the presence of DBU and $ZnBr_2$, it disappeared at 80^{o}C and reappeared at room temperature. Thus, we envision the formation of **3**-$ZrBr_2$ at 80 ^{o}C.



a) **2** at room temperature, b) **2** with DBU at room temperature, c) **2** with DBU at 80^{o}C, d) **2** with DBU and $ZnBr_2$ at 80 ^{o}C, e) **2** with DBU and $ZnBr_2$ at room temperature

Figure 4. ^{1}H NMR spectra in DMF-d_7 at room temperature and 80 ^{o}C

Although the exact mechanism of this transformation is not clear at the moment, a plausible reaction mechanism was proposed on the basis of the experimental observations (Fig **5**).

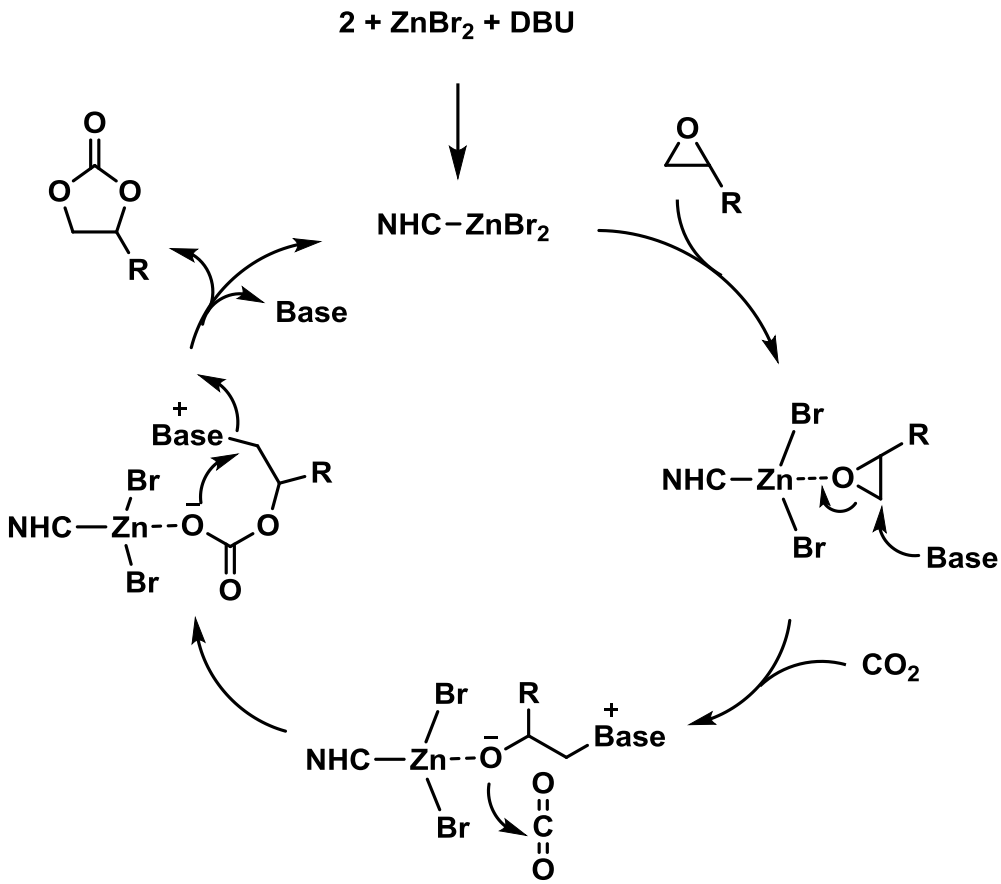


Figure 5. Plausible mechanism of cycloaddition of epoxide to CO_2

We envision that the NHC-$ZnBr_2$ species may play a major role in the coupling reaction at 80 ^oC, i.e., the reaction may be cocatalyzed by a Lewis base DBU and Lewis acid NHC-$ZnBr_2$ or $ZnBr_2$. The Lewis base and Lewis acid act together to open the epoxy ring and then react with CO_2 to afford the corresponding cyclic carbonates via a ring-opening and recyclization process. When a pre-synthesized polymer-NHC-$ZnBr_2$ complex was used as a catalyst, SC was obtained in 93% yield. This observation also supports the mechanism shown in fig **5**.

In conclusion, we examined an efficient poly(4-vinylimidazolium)s-DBU-$ZnBr_2$ catalyst system for the synthesis of cyclic carbonates by reacting terminal epoxides and internal epoxides with CO_2. Cyclic carbonate is the sole product in this reaction. Efforts are underway to elucidate the mechanistic details of the reaction and extend the applications of the catalyst system.

3. Experimental Section

General

All solvents were obtained by passing through activated alumina columns of solvent purification systems from Glass Contour. n-Hexanes and ethyl acetate were used without further purification. Reagents were purchased from Sigma-Aldrich, Alfa Aesar, Acros, and TCI and were used as received. HPLC grade water and DMF were used and acetonitrile was dried over ultra pure purification solvent system before use. Reactions were carried out in a flame -dried glassware equipped with a stirring bar and capped with a rubber septum under N_2, unless otherwise indicated. Elevated temperatures were maintained in thermostat-controlled oil baths. CO_2 (purity >99.999) was used. Workup procedures were done in air. Flash chromatography was carried out on Merck 60 silica gel (230 – 400 mesh). IR spectra were measured on a Thermo Scientific Nicolet 6700 spectrometer. ^1H and ^{13}C NMR spectra were recorded with Bruker (300 MHz) and Varian spectrometer (400 MHz) spectrometer. ^1H NMR spectra were referenced to residual TMS (0 ppm) except D_2O (solvent reference, 4.79 ppm) and DMF-d_7 (solvent reference, 8.03 ppm) and reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, dd = doublet of doublets, ddd = doublet of doublet of doublets, dt = doublets of triplets, td = triplet of doublets, qd = quertet of doublets, br s = broad singlet, m = multiplet). Chemical shifts of the ^{13}C NMR spectra were measured relative to $CDCl_3$ (77.16 ppm).

General procedure for the synthesis of various mono-Subsitituent cyclic carbonates

Reactions were performed in a tube schlenk equipped with a stirring bar and capped with a rubber cap and the followings were placed in the tube in order: 1 mol% of catalyst (13 mg, 0.05 mmol), 1mol% of $ZnBr_2$ (12 mg, 0.05 mmol), 2mol% of DBU (15 μL, 0.1 mmol) and 1mL of DMF. while they are mixing together, tube was charged with CO_2 by balloon for 30 seconds. Then, mono-substitutied epoxide (5 mmol) and 2mL of DMF were put into the schlenk. The mixture was stirred at 80 °C for 10 h and CO_2 was provided by balloon (1 atm). The reaction mixture was added in methanol and catalysts were filtered and filtrate was concentrated under reduced pressure. Purification by flash chromatography on silica gel with *n*-hexane and ethyl acetate afford cyclic carbonates. The cyclic carbonate products were characterized by ^{1}H NMR, ^{13}C NMR, IR and HRMS.

General procedure for the synthesis of various di-Subsitituent cyclic carbonates

Reactions werer carried out in 30mL autoclave eqipped with a magnetic stirrer. For a typical catalytic reaction, the catalyst (50 mg, 0.2 mmol), $ZnBr_2$ (45 mg, 0.2 mmol), DBU (60 μL, 0.4 mmol), appropriate expoxide (5 mmol) and 4mL of DMF were added to the autoclave. Water should be excluded to avoid side reaction, anhydrous DMF(99.8%) was purchased from aldrich and used. The autoclave was then charged to three cycles of pressurization and depressurization with CO_2 (5 atm). Then the

autoclave was placed under 10 atm and heated to 90 °C. After 24 hr, the autoclave was cooled to room temperature, depressurized. catalyst was seperated by filtration and the product was purified by flash column chromatography on silica gel with *n*-hexane and ethyl acetate afford cyclic carbonates. The cyclic carbonate products were characterized by ^{1}H NMR, ^{13}C NMR, IR and HRMS.

Recycling test

A Schlenk tube was charged with 2 mol% of catalyst (26 mg, 0.1 mmol), 2 mol% of $ZnBr_2$ (24 mg, 0.1 mmol), 4 mol% of DBU (30 μL, 0.2 mmol) and 1mL of DMF. while they are mixing together, tube was charged with CO_2 by a balloon for 30 seconds. Then, mono-substitutied epoxide (5 mmol) and 2 mL of DMF were put into the schlenk and provided CO_2 from a balloon. After stirring for 10 h at 80 °C, the polymer catalyst was successfully recovered by precipitation from the reaction mixture by addition of methanol. The solvents were evaporated from the filtrated, and the residue was purified by flash column chromatograpy. The recovered catalyst were used with 2 mol% of $ZnBr_2$, 4 mol% of DBU and 3 mL of DMF. The catalytic performance of poly(NHC)-Zn complex was well maintained during the catalyst reuse eight times, leading to carbonate in a range of 91-99% isolated yields.

Turn over number (TON) test

With fixed amounts of precatalyst **2** (13 mg, 0.05 mmol), $ZnBr_2$ (12 mg, 0.05 mmol) and DBU (15 μL, 0.1 mmol) in 3mL of DMF, the amount of styrene oxide was increased from 5 mmol to 25 mmol with 5 mmol of intervals in each step. The reactions were carried out at 80 °C in the presence of a CO_2 balloon.

Cat. Loading (%)	Isolated Yield (%)	TON
1	94	94
0.5	86	172
0.25	78	312
0.2	64	320

Preparation of Poly(NHC)-CO_2 Complex

The poly(NHC) (75 mg, 0.3 mmol), DBU (90 μL, 0.6 mmol) and 3 ml of DMF were added into a flame-dried tube schlenk equipped with a magnetic stirrier. The flask was charged with carbon dioxide by a balloon and the reaction mixture was stirred at 80 °C for 7 h. Then, acetone was added to the reaction mixture to precipitate. The precipitate, poly(NHC)-CO_2 complex, was filtered and dried under vacuum. After drying under vacuum, the complex was obtained as a yellowish solid. Yield: 96%. IR(ATR): 1656cm^{-1} (ν C=O).

Characterization of products

3-CO_2: ^{1}H NMR (400 MHz, D_2O) δ 7.17-7.66 (br s, 1 H), 3.38-4.12 (br s, 6 H), 3.11-3.38 (br s, 1 H), 2.38-2.64 (br s, 2 H) ppm. ^{13}C NMR (100 MHz, D_2O) δ 157.0 (C=O, bs s), 140.36 (br s), 136.66 (br s), 120.37 (br s), 39.8 (br s), 34.3 (br s), 30.6 (br s) ppm.

2a: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.45 – 7.37 (m, 3 H), 7.37 – 7.30 (m, 2 H), 5.65 (t, *J* = 8.0 Hz, 1 H), 4.80 – 4.74 (m, 1 H), 4.29 (dd, *J* = 8.7, 7.8 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.8, 135.7, 129.5, 129.0, 125.8, 77.9, 71.0 ppm. HRMS (EI) calc. for [$C_9H_8O_3$]: 164.0473, found: 164.0474; IR (neat): 1771 cm^{-1} (C=O); white solid.

2b: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33 (dt, *J* = 14.1, 7.0 Hz, 3 H), 7.22 (d, *J* = 6.8 Hz, 2 H), 4.98 – 4.89 (m, 1 H), 4.44 (t, *J* = 8.2 Hz, 1 H), 4.18 (dd, *J* = 8.5, 7.0 Hz, 1 H), 3.17 (dd, *J* = 14.2, 6.2 Hz, 1 H), 2.99 (dd, *J* = 14.2, 6.7 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.9, 134.0, 129.4, 129.0, 127.6, 76.9, 68.5, 39.6 ppm. HRMS (EI) calc. for [$C_{10}H_{10}O_3$]: 178.0630, found: 178.0632; IR (neat): 1790 cm^{-1} (C=O); colorless oil.

2c: ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.00 (qd, *J* = 9.2, 5.5 Hz, 1 H), 4.61 (q, *J* = 8.4 Hz, 1 H), 4.42 (dd, *J* = 8.8, 5.7 Hz, 1 H), 3.86 – 3.73 (m, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.4, 74.4, 67.0, 43.9 ppm. HRMS (EI) calc. for [$C_4H_5ClO_3$]: 135.9927, found: 135.9928; IR (neat): 1780cm^{-1} (C=O); yellowish oil.

2d: ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.82 (ddd, *J* = 11.3, 6.6, 3.2 Hz, 1 H), 4.59 – 4.43 (m, 2 H), 4.00 (ddd, *J* = 12.8, 5.0, 2.9 Hz, 1 H), 3.72 (ddd, *J* = 12.8, 6.6, 3.4 Hz, 1

H), 2.80 (br s, 1 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.5, 76.8, 65.9, 61.7 ppm. HRMS (FAB) calc. for [$C_4H_7O_4$]: 119.0344, found: 119.0347; IR (neat): 3430 cm^{-1} (br,OH), 1768 cm^{-1} (C=O); yellow oil.

2e: ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.73 (qd, *J* = 7.5, 5.5 Hz, 1 H), 4.55 (td, *J* = 8.3, 0.8 Hz, 1 H), 4.11 – 4.05 (m, 1 H), 1.85 – 1.76 (m, 1 H), 1.75 – 1.66 (m, 1 H), 1.49 – 1.32 (m, 4 H), 0.93 (dd, *J* = 10.1, 3.9 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.1, 77.1, 69.4, 33.4, 26.4, 22.2, 13.7 ppm. HRMS (FAB) calc. for [$C_7H_{13}O_3$]: 145.0865, found: 145.0866; IR (neat): 1787cm^{-1} (C=O); yellowish oil.

2f: ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.73 (qd, *J* = 7.5, 5.5 Hz, 1 H), 4.55 (td, *J* = 8.3, 0.8 Hz, 1 H), 4.11 – 4.05 (m, 1 H), 1.85 – 1.76 (m, 1 H), 1.75 – 1.66 (m, 1 H), 1.49 – 1.32 (m, 4 H), 0.93 (dd, *J* = 10.1, 3.9 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.1, 77.1, 69.4, 33.4, 26.4, 22.2, 13.7 ppm. HRMS (FAB) calc. for [$C_7H_{13}O_3$]: 145.0865, found: 145.0866; IR (neat): 1787cm^{-1} (C=O); yellowish oil.

2g: ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.65 (qd, *J* = 7.5, 5.4 Hz, 1 H), 4.47 (t, *J* = 8.1 Hz, 1 H), 4.00 (t, *J* = 7.8 Hz, 1 H), 1.77 – 1.67 (m, 1 H), 1.67 – 1.57 (m, 1 H), 1.45 – 1.35 (m, 1 H), 1.27 (dd, *J* = 23.9, 19.2 Hz, 7 H), 0.81 (d, *J* = 6.5 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.1, 77.1, 69.4, 33.8, 31.5, 28.7, 24.3, 22.4, 13.9 ppm. HRMS (FAB) calc. for [$C_9H_{17}O_3$]:173.1178, found:173.1178; IR (neat): 1792 cm^{-1} (C=O), yellowish oil.

2h: ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.95 – 4.83 (m, 1 H), 4.62 – 4.55 (m, 1 H), 4.08 – 4.01 (m, 1 H), 1.52 – 1.48 (m, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.1, 73.6, 70.6, 19.3 ppm. HRMS (EI) calc. for [$C_4H_6O_3$]: 102.0317, found: 102.0315; IR (neat): 1782 cm^{-1} (C=O); yellowish oil.

2i: ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.86 – 5.72 (m, 1 H), 5.14 – 5.02 (m, 2 H), 4.78 – 4.69 (m, 1 H), 4.57 – 4.51 (m, 1 H), 4.12 – 4.06 (m, 1 H), 2.30 – 2.15 (m, 2 H), 1.93 (ddd, *J* = 16.8, 10.0, 4.0 Hz, 1 H), 1.83 – 1.74 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.0, 136.1, 116.4, 76.4, 69.4, 33.1, 28.7 ppm. HRMS (EI) calc. for [$C_7H_{10}O_3$]: 142.0630, found: 142.0628; IR (neat): 1786 cm^{-1} (C=O); yellowish oil.

2j: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58 (d, *J* = 8.5 Hz, 2 H), 7.25 (d, *J* = 8.4 Hz, 2 H), 5.65 (t, *J* = 8.0 Hz, 1 H), 4.81 (t, *J* = 8.4 Hz, 1 H), 4.33 – 4.28 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.6, 134.9, 132.5, 127.6, 123.9, 77.3, 71.0 ppm. HRMS (EI) calc. for [$C_9H_7BrO_3$]: 241.9579, found: 241.9576; IR (neat): 1787 cm^{-1} (C=O); pale-yellow solid.

2k: ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.89 – 6.80 (m, 4 H), 5.04 – 4.95 (m, 1 H), 4.60 (t, *J* = 8.4 Hz, 1 H), 4.53 (dd, *J* = 8.5, 5.9 Hz, 1 H), 4.18 (dd, *J* = 10.6, 4.2 Hz, 1 H), 4.10 (dd, *J* = 10.6, 3.6 Hz, 1 H), 3.77 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.9, 154.5, 151.9, 115.7, 114.6, 74.4, 67.7, 66.1, 55.6 ppm. HRMS (EI) calc. for [$C_{11}H_{12}O_5$]: 224.0685, found: 224.0687; IR (neat): 1776 cm^{-1} (C=O); white solid.

2l: ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.11 (s, 2 H), 1.46 (s, 6 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.6, 81.8, 75.3, 25.8 ppm. HRMS (EI) calc. for [$C_5H_8O_3$]: 116.0473, found: 116.0475; IR (neat): 1787 cm^{-1} (C=O); yellowish oil.

2m: ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.30 (dt, *J* = 5.8, 4.0 Hz, 2 H), 1.41 – 1.36 (m, 6 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.4, 79.8, 18.1 ppm. HRMS (EI) calc. for [$C_5H_8O_3$]: 116.0473, found: 116.0474; IR (neat): 1774 cm^{-1} (C=O); white solid.

2n: ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.71 – 4.61 (m, 2 H), 1.89 – 1.76 (m, 4 H), 1.57

– 1.48 (m, 2 H), 1.43 – 1.34 (m, 2 H)ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.2, 75.6, 26.4, 18.8 ppm. HRMS (EI) calc. for [$C_7H_{10}O_3$]: 142.0630, found: 142.0629; IR (neat): 1783 cm^{-1} (C=O); colorless solid.

2o: ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.07 (d, *J* = 2.2 Hz, 2 H), 2.08 – 2.00 (m, 2 H), 1.78 – 1.59 (m, 4 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.4, 81.8, 32.8, 21.3 ppm. HRMS (EI) calc. for [$C_6H_8O_3$]: 128.0473, found: 128.0472; IR (neat): 1792 cm^{-1} (C=O); white solid.

2p: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42 (dd, *J* = 4.1, 2.3 Hz, 6 H), 7.33 – 7.27 (m, 4 H), 5.42 (s, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.1, 134.7, 129.8, 129.2, 126.1, 85.3 ppm. HRMS (EI) calc. for [$C_{15}H_{12}O_3$]: 240.0786, found: 240.0785; IR (neat): 1811 cm^{-1} (C=O); white solid.

2q: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.49 – 7.42 (m, 3 H), 7.42 – 7.36 (m, 2 H), 5.66 (d, *J* = 5.7 Hz, 1 H), 4.91 (d, *J* = 5.8 Hz, 1 H), 4.35 (qd, *J* = 7.1, 3.1 Hz, 2 H), 1.34 (t, *J* = 7.2 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.7, 153.1, 135.4, 129.8, 129.2, 125.5, 79.9, 79.0, 62.9, 13.9 ppm. HRMS (EI) calc. for [$C_{12}H_{12}O_5$]: 236.0685, found: 236.0686; IR (neat): 1809, 1756 cm^{-1} (C=O); yellowish oil.

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Part II.

Base-catalyzed organic reactions

General

Research background

Carbon–carbon[1] and carbon–heteroatom[2] bond formations are the most important methodologies which give tremendous applications in synthetic organic chemistry as regarded as the most powerful tools. Most of the bond formations are carried out via transition metal catalyst. The conventional bond formation is cross-coupling[3] reactions that aryl halides act as electrophiles and organometallic reagents act as nucleophiles. In addition, recent developments have emerged to the bond formation by C–H bonds activation for chemical cost and atom economy/ efficiency.[4] Even though transition metal-catalyzed coupling reactions have been developed as one of the powerful tools for the bond formations, there are some drawbacks in the metal-mediate catalytic systems.

The first proplem is that transition metal catalysts are usually expensive[5], and also coordinating ligands are sometimes even more expensive. Second, most of the transition metals are toxic which could contaminate the desired product. Thus, removal of trace amounts of transition-metal impurities from the products is challenging and crucial especially in the pharmaceutical business.[6] Third, transition metal catalysts are mainly sensitive to oxygen (O_2) and moisture which is hard to handle. Thus, efforts have been towards to the development of transition metal-free reactions which overcome the drawbaks of the metal-mediated reactions.

Given these requirements, metal-free approaches are considered as one of the greatest potential reactions.[7] In this regard, base catalysis are of interest in

economically/ eco-friendly perspectives.[8] Because base catalysts are usually inexpensive, available, non-toxic and air stable. Besides toxic metal catalyst and impurities could be avoided by base catalysts. Thus, base catalyst with readily available starting materials could provide new synthetic challenges in green chemistry aspects.

On the basis of the concept on base catalyzed-reaction, **part II** will discuss of two reactions catalyzed by common base. The first example is the three component reaction to synthesize oxazolidiones[9a] with potassium phosphate (K_3PO_4) as a base catalyst and the second example is synthesis of unsymmetric flourene[9b] catalyzed by potassium phosphate dibasic (K_2HPO_4). Both examples are using catalytic amount of commercially available common base and simple starting materials. These examples provide a new synthetic method for high efficiency and scalable, thus ecomonic/eco-friendly synthetic challenges have been demonstrated.

Chapter 1.

Potassium Phosphate-Catalyzed One-pot Synthesis of 3-Aryl-2-oxazolidinones from Epoxides, Amines, and an Atmospheric Carbon Dioxide

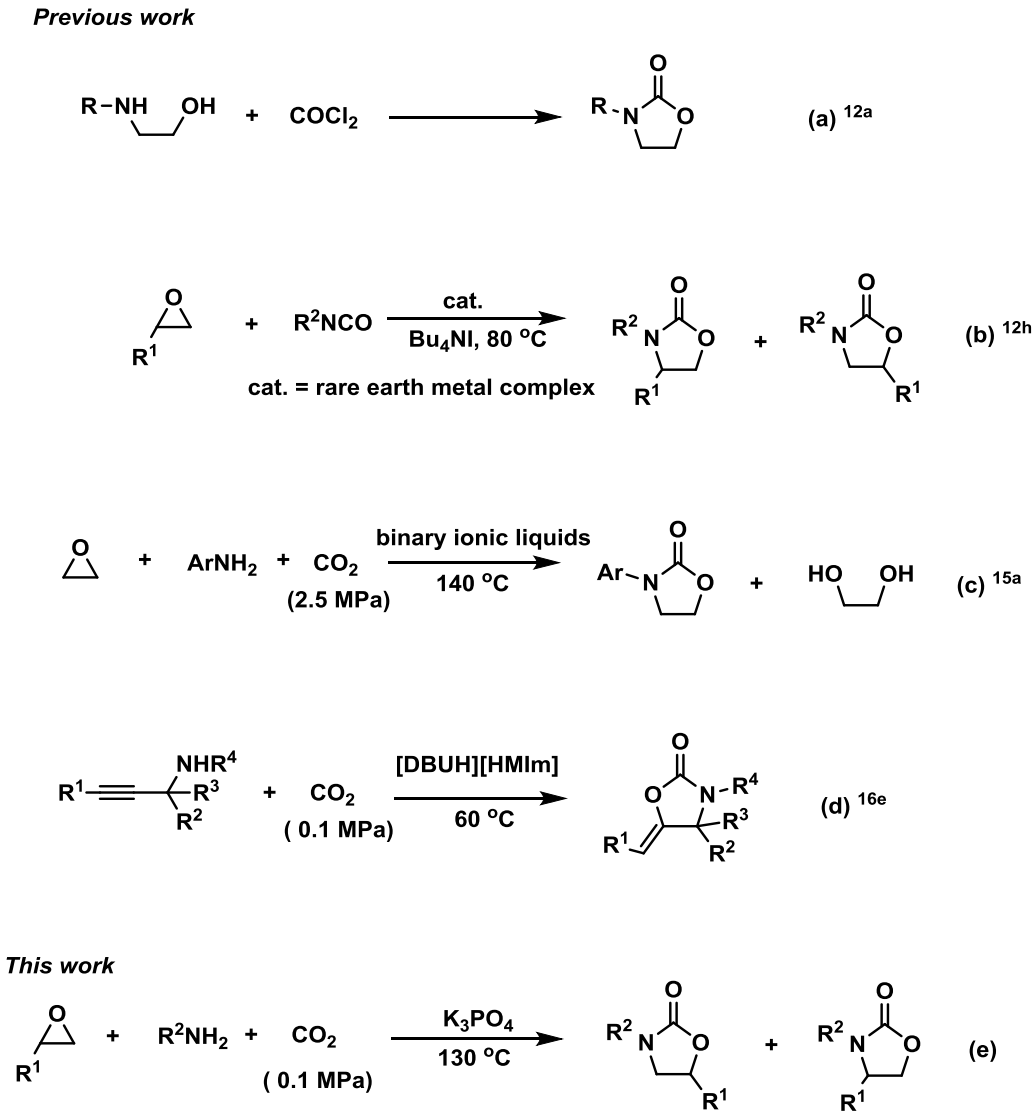
1. Introduction

Atmospheric levels of CO_2 have been rapidly increased since the industrial revolution. Carbon dioxide is now considered a primary cause of global warming. Therefore, efficient methods that convert carbon dioxide into valuable chemicals have attracted much attention. Carbon dioxide is consumed as a reactant in the production of urea, with a smaller fraction used to produce methanol. Therefore, intensive research on CO_2 has been carried out.[10] However, most developed reactions have been carried out in the presence of strong bases and/or transition metal complexes under high-pressure of CO_2.

Oxazolidinones are five-membered heterocyclic compounds that contain nitrogen and oxygen. Owing to their utility in organic synthesis and pharmaceutical, and agricultural industries, oxazolidinone preparation has been well studied.[11] The conventional synthetic methods use phosgene or isocyanate as carbonyl precursors (Scheme **1**, a and b).[12] However, the toxicity of these starting materials is not compatible with green chemistry. Alternative synthetic methods that use CO_2 or cyclic carbonates as carbonyl precursors in the presence of metal salts have also been reported.[13,14] Among the reported synthetic methods, the three-component cycloaddition of CO_2, epoxide, and primary amines affording 2-oxazolidinones,[15] are the most interesting and promising synthetic method with regard to developing CO_2 as carbon source. Most of the known reactions involving the use of carbon dioxide as a CO surrogate are conducted under high pressure of carbon dioxide and/or in the presence of some precious metal catalysts. Gao et al.[15] reported a three-component reaction using binary ionic liquids as catalysts under 25 atm of CO_2

(Scheme **1**, c). They proposed amino alcohols and cyclic carbonates as reaction intermediates. Some reported the synthesis of oxazolidinones from propargylamines under atmospheric carbon dioxide (Scheme **1**, d).[16] Therefore, developing (or identifying) a new route to oxazolidinone structures using readily available starting materials in the absence of toxic and/or precious metal catalysts under mild reaction conditions is a synthetic challenge (Scheme **1**, e).

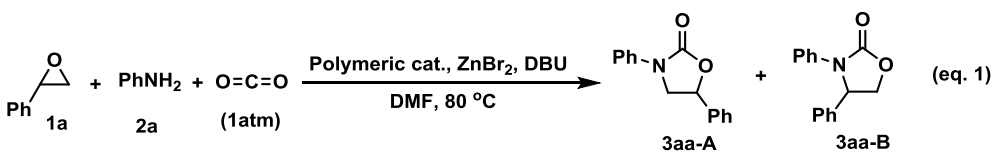
K_3PO_4 has been widely used as a catalyst, additive, and base in organic reactions.[17-19] It has many advantages such as being non-toxic, inexpensive, soluble in organic solvents, and is readily available. Furthermore, there is no potential residual metal contamination in products. Among many useful K_3PO_4-catalyzed reactions, the carboxylation of amines[20] attracted our attention. However, the reaction conditions (NMP as solvent, 170 ^oC, 5 MPa CO_2) were too harsh to be applicable to standard laboratory facilities. This exciting result prompted us to investigate the use of readily available and mildly basic K_3PO_4 in different carboxylation reactions. Herein we wish to report the reslt that using K_3PO_4 as a catalyst in the synthesis of oxazolidinones from epoxides, amines, and atmospheric carbon dioxide. Aryl isocyanate and 1,2-aminoalcohol were used as key intermediates. Thus, an eco-friendly catalytic system without transition metal catalyst and toxic reagents has been developed in this study. As far as we are aware, this is the first base-metal catalyzed incorporation of atmospheric CO_2 to oxazolidinones.



Scheme 1. Syntheses of oxazolidiones

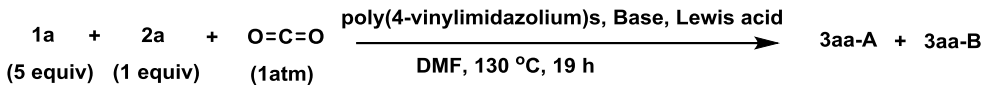
2. Result and Discussion

The K_3PO_4-catalyzed synthesis of 3-aryl-2-oxazolidinones was discovered in a study on the use of polymer catalysts for the synthesis of oxazolidinones (eq 1). Aniline and styrene oxide were chosen as starting materials for reaction condition optimization. Initially, the reaction was carried out under the reaction conditions (1 mol% polymer catalyst, 1 mol% $ZnBr_2$ as the Lewis acid, 2mol% DBU as the base, DMF as the solvent, at 80 ^oC for 10 h) adopted from a previous work on the poly(4-vinylimidazolium)s/DBU-$ZnBr_2$-catalyzed cycloaddition of carbon dioxide to epoxide.[21]



First, the reaction conditions were optimized, including, base, Lewis acid, reaction temperature, and solvent to maximize the yield of oxazolidinone (Table **1**). The study was initially performed under the following reaction conditions: 10 mol% catalyst, $ZnBr_2$ as the Lewis acid, DBU as the base, DMF as the solvent at 130 ^oC. An overall yield 13 % yield was observed (Table 1, entry 1). After screening the Lewis acids, $Zn(OAc)_2$ was found to show the best performance. Next, various bases were tested including DBU, K_2CO_3, and K_3PO_4, The best yield was observed when K_3PO_4 was used (entry 8, 98 % yield). Changing the ratio or solvent afforded a slightly lower yield (entries 10-12). Thus, the optimized reaction conditions were as followed: 10 mol% of catalyst, 20 mol% of K_3PO_4, 10 mol% of $ZnOAc_2$, 130 ^oC under atmospheric carbon dioxide.

Table 1. Screening the reaction conditions [a]

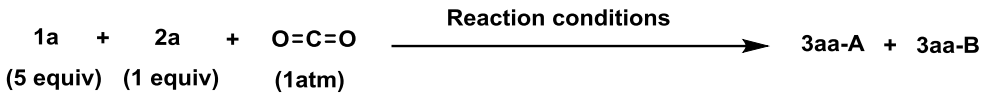


Entry	Catalyst (mol%)	Base (mol%)	Lewis acid (mol%)	Isolated yield (%)		
				3aa-A	**3aa-B**	Total
1	10	DBU (20)	$ZnBr_2$ (10)	3	10	13
2	10	DBU (20)	ZnI_2 (10)	-	2	2
3	10	DBU (20)	$Zn(OTf)_2$ (10)	7	5	12
4	10	DBU (20)	$ZnCl_2$ (10)	4	6	10
5	10	DBU (20)	$Zn(OAc)_2$ (10)	16	48	64
6	10	DBN (20)	$Zn(OAc)_2$ (10)	12	50	62
7	10	K_2CO_3 (20)	$Zn(OAc)_2$ (10)	48	38	86
8	10	K_3PO_4 (20)	$Zn(OAc)_2$ (10)	30	68	98
9[b]	10	K_3PO_4 (20)	$Zn(OAc)_2$ (10)	23	58	81
10[c]	10	K_3PO_4 (20)	$Zn(OAc)_2$ (10)	34	58	92
11[d]	10	K_3PO_4 (20)	$Zn(OAc)_2$ (10)	15	20	35
12[e]	10	K_3PO_4 (20)	$Zn(OAc)_2$ (10)	20	53	73

[a] Reaction conditions: poly(4-vinylimidazolium)s, base, zinc source was added with 1mL of solvent. Then styrene oxide (5mmol) and aniline (1mmol) were reacted at 120 °C under atmospheric carbon dioxide. [b] DMA was used. [c] At 120 °C. [d] At 110 °C. [d] The ratio of **1a:2a** = 4:1.

We then explored the effect of an individual additive including the catalyst, Lewis acid and base in the synthesis of oxazolidinones (Table **2**). Surprisingly, the reaction underwent quite well even without $Zn(OAc)_2$ (entry 2, 74 %). This observation suggested that the reaction could activate carbon dioxide without the help of Lewis acid. The reaction with $Zn(OAc)_2$ and K_3PO_4 showed poor yield (entry 3, 21%). It was noteworthy that the reaction occurred in the presence of potassium phosphate (entry 4). Therefore, potassium phosphate itself could activate atmospheric carbon dioxide to form oxazolidinone.

Table 2. Control experiments

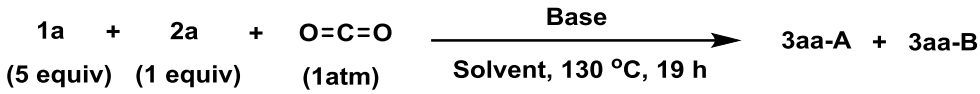


Entry	Catalyst	$Zn(OAc)_2$	K_3PO_4	Isolated yield (%)		
				3aa-A	**3aa-B**	Total
1	O	O	O	68	30	98
2	O	X	O	57	17	74
3	X	O	O	12	9	21
4	X	X	O	76	22	98
5	X	O	X		N.R.	

Therefore, we attempted to optimize the reaction conditions in the presence of a base catalyst. First, conditions such as a reaction temperature, solvent, and base catalyst, were optimized to obtain the maximum oxazolidinone yields (Table **3**). Initially, the following reaction conditions were used: 20 mol% base catalyst in DMF at 130 ^{o}C for 19 h. To improve the yield, different bases were used (entries 1-9). The reaction yield was highly sensitive to the base. However, catalyst basicity was not the sole factor in determining its activity. Among bases, the best yield was observed for K_3PO_4 (entry 7). In the presence of K_3PO_4, 3,5-diphenyl-1,3-oxazolidin-2-one (**3aa-A**) and 3,4-diphenyl-1,3-oxazolidin-2-one (**3aa-B**) were isolated in 76% and 22% yield, respectively. Thus, the overall yield was 98% with an **A**: **B** ratio of 3.5: 1. In reactions of a monosubstituted epoxide, such as styrene oxide with amines, there is regioselectivitiy problem. In general, epoxide ring-opening occurs at the less hindered carbon atom, giving 3,5-disubstituted oxazolidinone (**A**) as the major product and 3,4−isomer (**B**) as the minor product. For example, the **A**: **B** ratio was 1.75:1 when the reaction of phenyl isocyanate with aniline was conducted in the presence of (salcen)Cr^{III} and PPh_3O.[22] Moreover, **A** and **B** were formed in ratios of 1:1.9-2.5 in the presence of bimetallic aluminium salen or (salen)V^{V}/ tetrabutylammonium bromide catalysts.[23] Thus, a relatively high regioselectivity was observed in the presence of K_3PO_4. Bases K_2CO_3, DBU, and KOH similarly exhibited high activities and high regioselectivities (3.2:1 - 4.9:1) (entries 1, 5, and 6). Cs_2CO_3 also showed good reactivity (74%) with a high **A**: **B** ratio (3.1:1). However, surprisingly poor activity was observed when using Na_3PO_4 or K_2HPO_4 (entries 8-9). The necessity of base catalysts in the reaction was confirmed when no reaction was observed in their absence (entry 10). The effect of various solvents on

the reaction system was also examined (entries 7 and 11-13). DMSO and DMA were quite efficient (entries 11 and 13), while toluene was proven to be inefficient for this transformation (entry 12). When the reaction temperature was lowered, no improvement in yield was observed (entry 14). DMF gave the best result and was used in further studies. Decreasing the amount of styrene oxide or K_3PO_4 led to a decrease in reaction yield (entries 15 and 16). Reducing the reaction time to 16 h resulted in a lower yield of 86% (**A**: **B** = 71%: 15%) (entry 17). Therefore, the optimum reaction conditions were established as follows: 20 mol% K_3PO_4, 1 mmol amine, 5 mmol aryl epoxide, 2.0 mL DMF, 1 atm CO_2 (balloon), 130℃, and 19 h.

Table 3. Screening the reaction conditions [a]

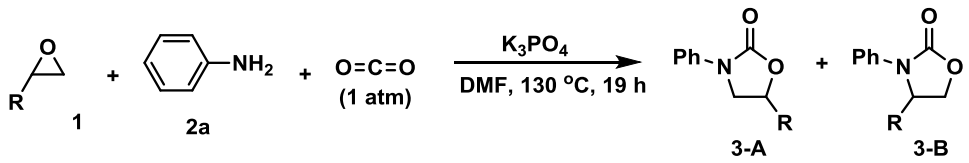


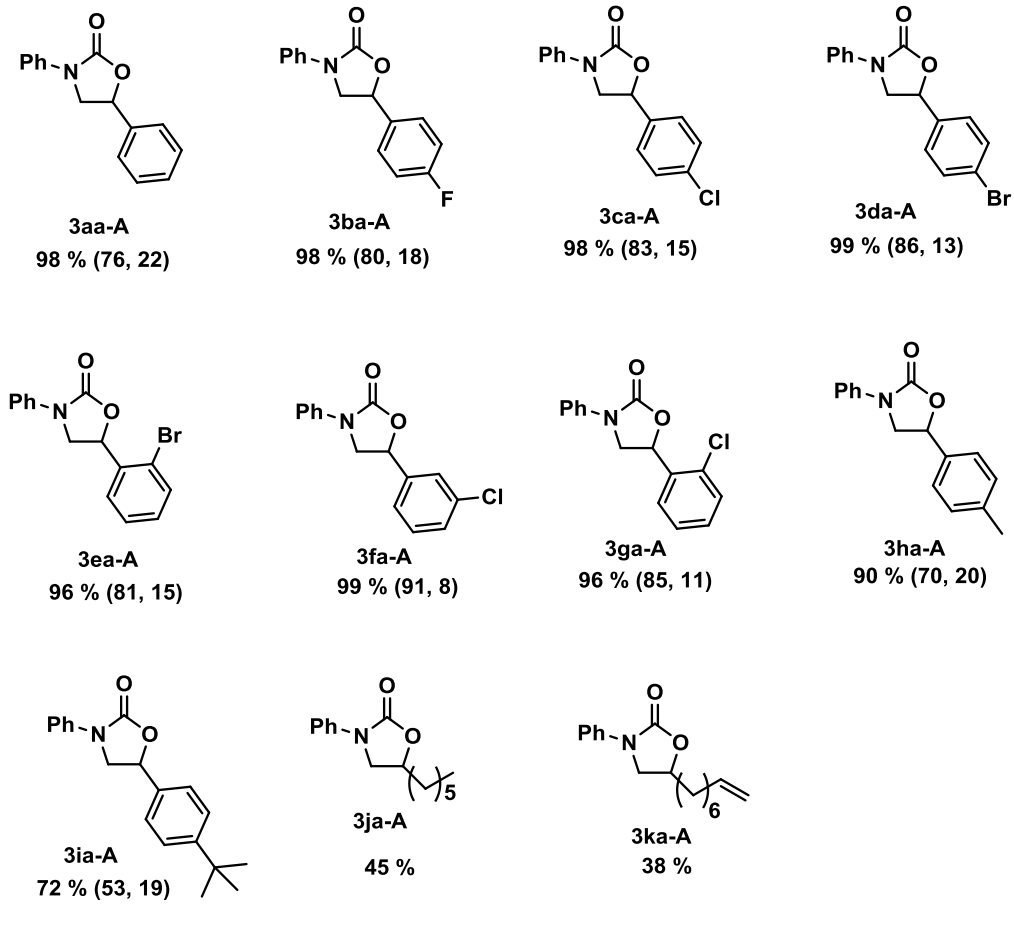
Entry	Solvent	Base (mol%)	Isolated yield (%)		
			3aa-A	**3aa-B**	Total
1	DMF	K_2CO_3 (20)	61	19	80
2	DMF	Na_2CO_3 (20)	6	2	8
3	DMF	Cs_2CO_3 (20)	57	17	74
4	DMF	$KHCO_3$	13	6	19
5	DMF	DBU (20)	69	15	84
6	DMF	KOH(20)	74	15	89
7	DMF	K_3PO_4 (20)	76	22	98
8	DMF	Na_3PO_4 (20)	3	3	6
9	DMF	K_2HPO_4 (20)	2	3	5
10	DMF	-	-	-	-
11	DMSO	K_3PO_4 (20)	68	18	86
12	Toluene	K_3PO_4 (20)	-	-	-
13	DMA	K_3PO_4 (20)	71	16	87
14[b]	DMF	$K_3PO_4$20)	61	14	75
15[c]	DMF	K_3PO_4 (20)	69	14	83
16	DMF	K_3PO_4 (15)	75	16	91
17[d]	DMF	K_3PO_4 (15)	71	15	86

[a] Reaction conditions: Base in with 2 mL of solvent, 5 mmol of styrene oxide, 1 mmol ofaniline at specified temperature under atmospheric carbon dioxide. [b] At 120 °C. [c] The ratio of **1a:2a** = 4:1. [d] For 16 h

With the optimized reaction conditions established, we explored the scope of this transformation (Table **4**). The nature of the aryl and aliphatic epoxides were explored first. Aryl epoxides (**1b**-**1d**) bearing a para-halo group (F, Cl, and Br) were excellent substrates, giving near-quantitative yields with high **A**: **B** ratios (4.4:1 − 6.6:1). Aryl epoxides (**1e**-**1g**) with meta- or ortho- halo group (Br and Cl) were still excellent substrates (96 − 99%) and gave high **A**: **B** ratio (5.4:1 − 11.4:1). When an electron donating group, such as methyl or *tert*-butyl, was introduced to the aryl group (**1h** and **1i**), the yield decreased. In particular, when a *tert*-butyl group was introduced at the para- position (**1i**), the yield decreased to 72% with an **A**: **B** ratio of 2.8: 1. Thus, the yield was highly dependent on the electronic effects of the aryl epoxide. The reaction was not restricted to aryl epoxides. However, high yields of oxazolidinones were not observed for aliphatic epoxides, presumably due to the low reactivity in the reaction with carbon dioxide to form cyclic carbonates (see the experimental section). Aliphatic epoxides with a long chain alkyl group (**1j** – **1k**) afforded a single regioisomer in 45% and 38% yields, respectively. The regioselectivity might be due to a steric reason.

Table 4. Cycloaddition of CO_2 with terminal epoxides and aniline [a]

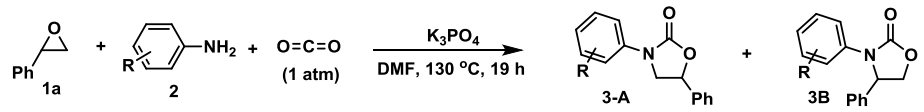


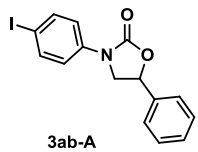


[a] Reaction conditions: 43 mg of K_3PO_4 in 1 mL of DMF, 5 mmol of styrene oxide derivatives, 1 mmol of aniline in 1 mL of DMF (total 2 mL of DMF) at 130 °C under atmospheric carbon dioxide. The data in parentheses are the yields of **A** and **B**, respectively.

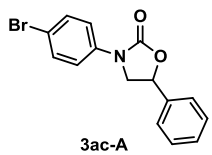
The reaction scope for aniline substrates was explored next (Table **5**). Various amines bearing either electron-donating (Me, OMe, Bu, OPh) or electron-withdrawing (Cl, Br, I, NO_2) meta- or para-substituents were also tested. In general, amines bearing electron-donating (**3ah**-**3aj**, and **3al,** 93-98%) and electron-withdrawing substituents (**3ab**-**3ae,** 92-95%) exception of para-nitroaniline (78%) were all tolerated in the reaction. Steric hindrance was to have a dramatic effect in the cases of 2-bromoaniline (**2f**), 3,5-dimethylaniline (**2k**), naphthalen-1-amine (**2m**). When 2-bromoaniline (**2f**) was used as an amine source under the optimized reaction conditions, oxazolidinone derivative **3af** was isolated in 38% with an **A**: **B** ratio of 3.2:1. However, lengthening the reaction time from 19 to 27 h gave an improved yield of 86%, with an **A**: **B** ratio of 3.8:1. When 3,5-dimethylaniline (**2k**) or naphthalen-1-amine (**2m**) were used as amines, the corresponding oxazolidinones were isolated in 80% (**3ak**, 4.0:1) and 85% (**3am**, 3.6:1) yields, respectively. Aliphatic amines, such as benzyl amine (**2n**) and octyl amine (**2o**), were good substrates, resulting in the corresponding oxazolidinones in 92% (**3an**) and 85% (**3ao**) yields, respectively. Interestingly, excellent regioselectivity was observed for *p*-nitroaniline (**2g**), benzyl amine (**2n**), and octyl amine (**2o**), with only the **A** isomer produced.

Table 5. Cycloaddition of CO_2 with various amines and styrene oxide [a]

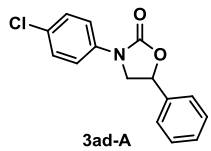




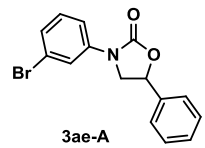
3ab-A
93 % (75, 18)



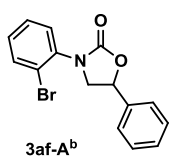
3ac-A
93 % (78, 15)



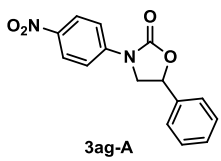
3ad-A
92 % (76, 16)



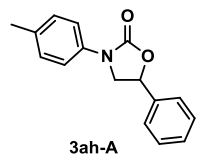
3ae-A
95 % (81, 14)



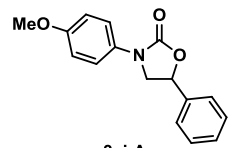
3af-A[b]
86 % (68, 18)



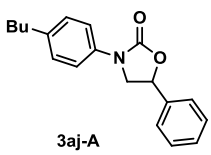
3ag-A
78 %



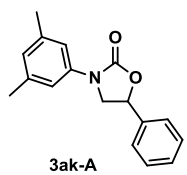
3ah-A
98 % (81, 17)



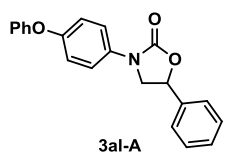
3ai-A
97 % (77, 20)



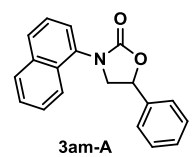
3aj-A
93 % (74, 19)



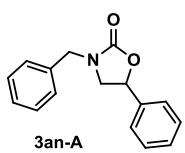
3ak-A
80 % (64, 16)



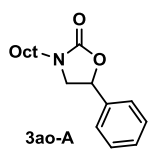
3al-A
98 % (79, 19)



3am-A
83 % (65, 18)



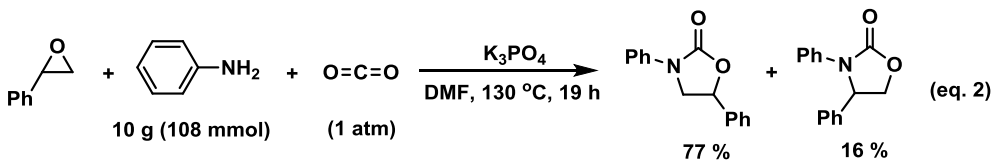
3an-A
92 %



3ao-A
85 %

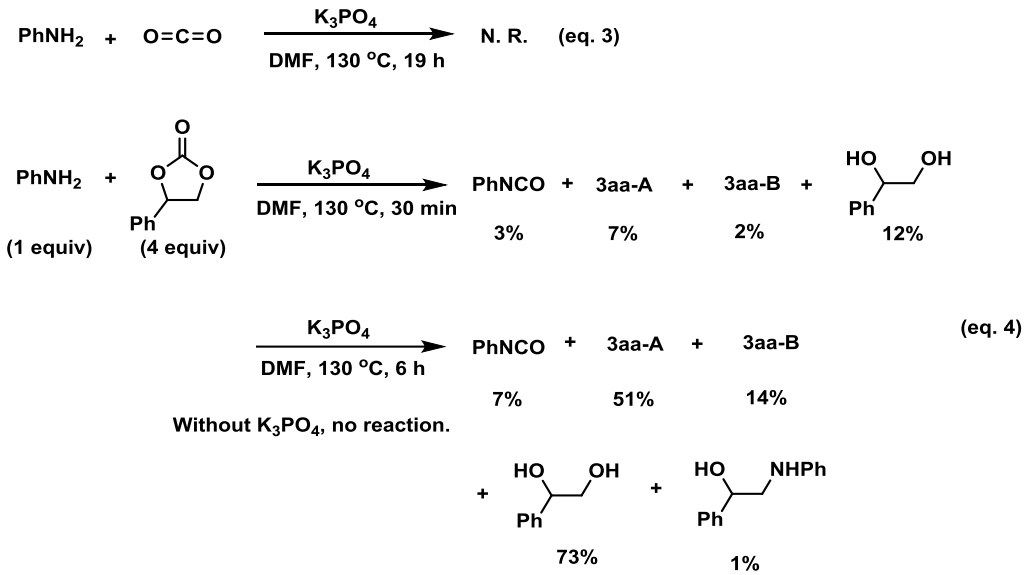
[a] Reaction conditions: 43 mg of K_3PO_4 in 1 mL of DMF, 5 mmol of styrene oxide, 1 mmol of amines with additional 1 mL of DMF(total 2 mL of DMF) at 130 °C under atmospheric carbon dioxide. The data in parentheses are the yields of **A** and **B**, respectively. [b] For 27 h

In addition, the reaction could be conducted on a 10-g-scale (10.0 g (108 mmol) of aniline, 93% yield, with an **A**: **B** = 77: 16) (eq 2).

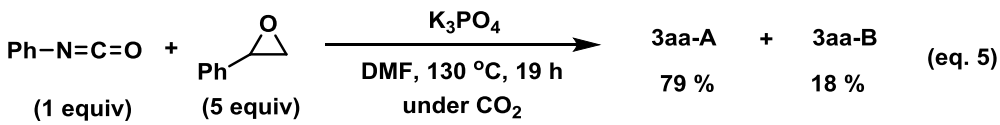


Scaling-up the procedure did not result in lower yields. Thus, notable features of the current method include: (i) a low cost catalyst, (ii) mild reaction conditions, (iii) simple operations, (iv) high efficiency, and (v) scalability.

Two possible paths for the synthesis of 3-aryl-2-oxazolidinones (**3**) from CO_2, aniline (**2a**) and styrene oxide (**1a**) could be proposed based on the formation of isocyanate from CO_2 and amine as well as the formation of amino alcohol from epoxide and amine. To determine whether phenyl isocyanate was generated under these reaction conditions, two experiments were conducted (eqs. 3 and 4). When aniline was reacted with carbon dioxide, no reaction was observed (eq 3), which confirmed that no phenylcarbamic acid was generated during the reaction. When aniline was reacted with styrene carbonate, phenyl isocyanate, oxazolidinones[24] **3aa-A** and **3aa-B**, and 1-phenylethan-1,2-diol were formed in 3%, 7%, 2%, and 13% yields, respectively, after 30 min (eq 4). As expected, no reaction was observed without K_3PO_4, and neither 1,2-aminoalcohol nor hydroxyurethane[25] was detected after 30 min. However, with a reaction time of 6 h, the formation of 1,2-aminoalcohol was observed (vide infra).

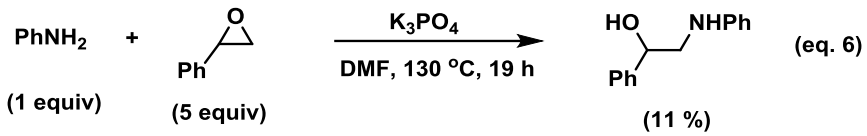


The following reactions, in eqs 5 and 6, were also studied.

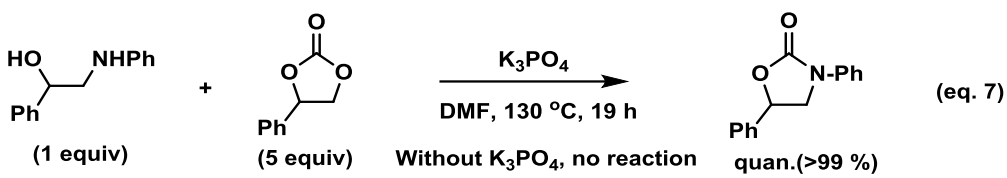


When phenyl isocyanate was reacted with styrene oxide in the presence or absence of carbon dioxide, the expected oxazolidinone was isolated in 97% (**A**: **B** = 4.4:1). The result obtained in the presence of carbon dioxide was almost identical to that obtained for the reaction of aniline and styrene oxide with carbon dioxide.

We studied whether the reaction of aniline with styrene oxide would generate 1,2-aminoalcohol in the presence of K_3PO_4 under a nitrogen atmosphere. Only 11 % of 1,2-aminoalcohol was formed and 80 % of aniline remained intact (eq 6).

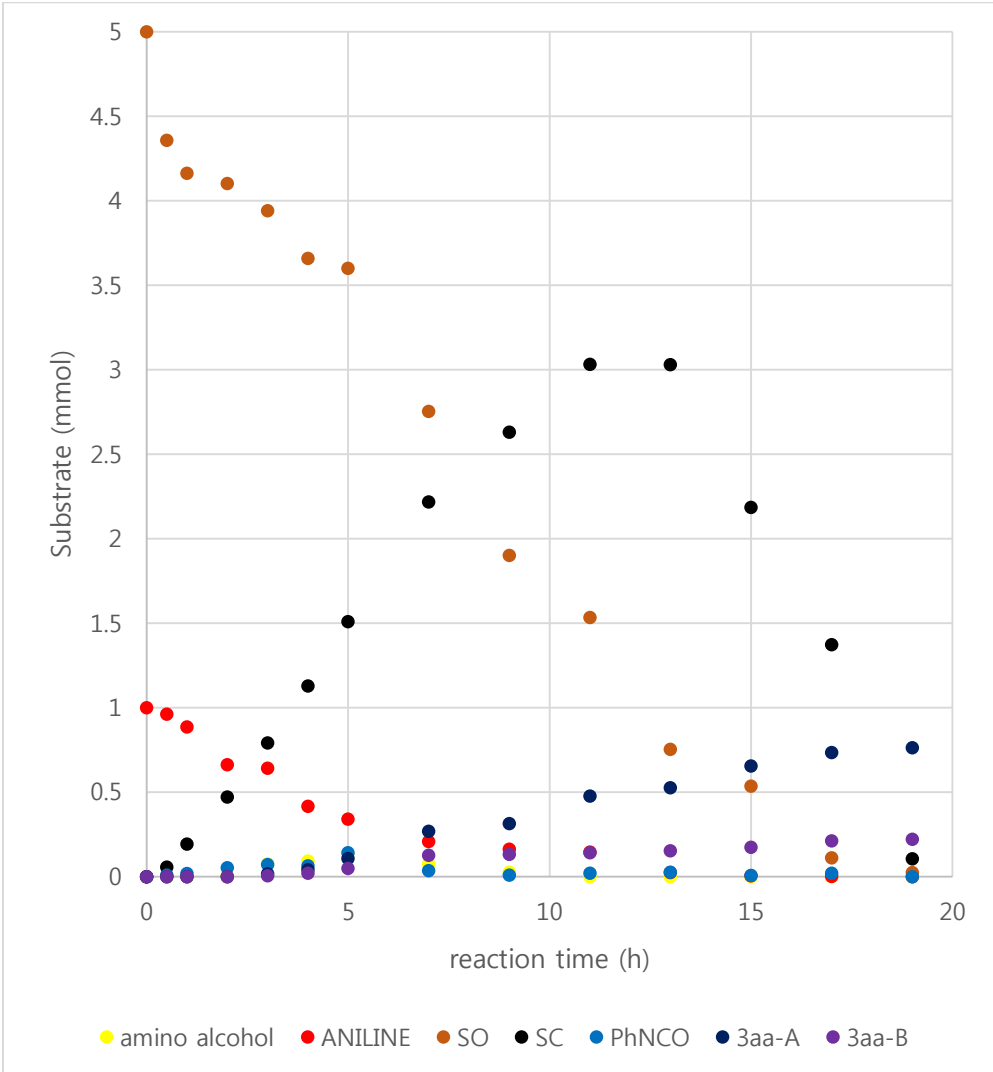


To determine the reactivity of 1,2-aminoalcohol under the optimized reaction conditions, it was reacted with styrene carbonate in the presence of K_3PO_4, which afforded 3,5-diphenyl-1,3-oxazolidin-2-one quantitatively (eq 7).[26]



We monitored the reaction intermediate generated in the synthesis of 3-aryl-2-oxazolidinones from styrene epoxide, aniline, and atmospheric carbon dioxide (Fig 1 and 2).[27]

Initially, a rapid consumption of styrene oxide and formation of styrene carbonate was observed. As time passed, the concentrations of phenyl isocyanate and amino alcohol slowly increased and then decreased. Phenyl isocyanate appeared for a longer period of the reaction time than 1,2-aminoalcohol. According to GC-Mass analysis, 1-phenyl-2-(phenylamino)ethan-1-ol was formed as a single regio-isomer and its reaction with styrene carbonate would lead to the formation of 3,5-diphenyl-1,3-oxazolidin-2-one.



(SO = styrene oxide; SC = styrene carbonate)

Figure 1. Reaction profile for the oxazolidione synthesis from styrene oxide, aniline, and CO_2

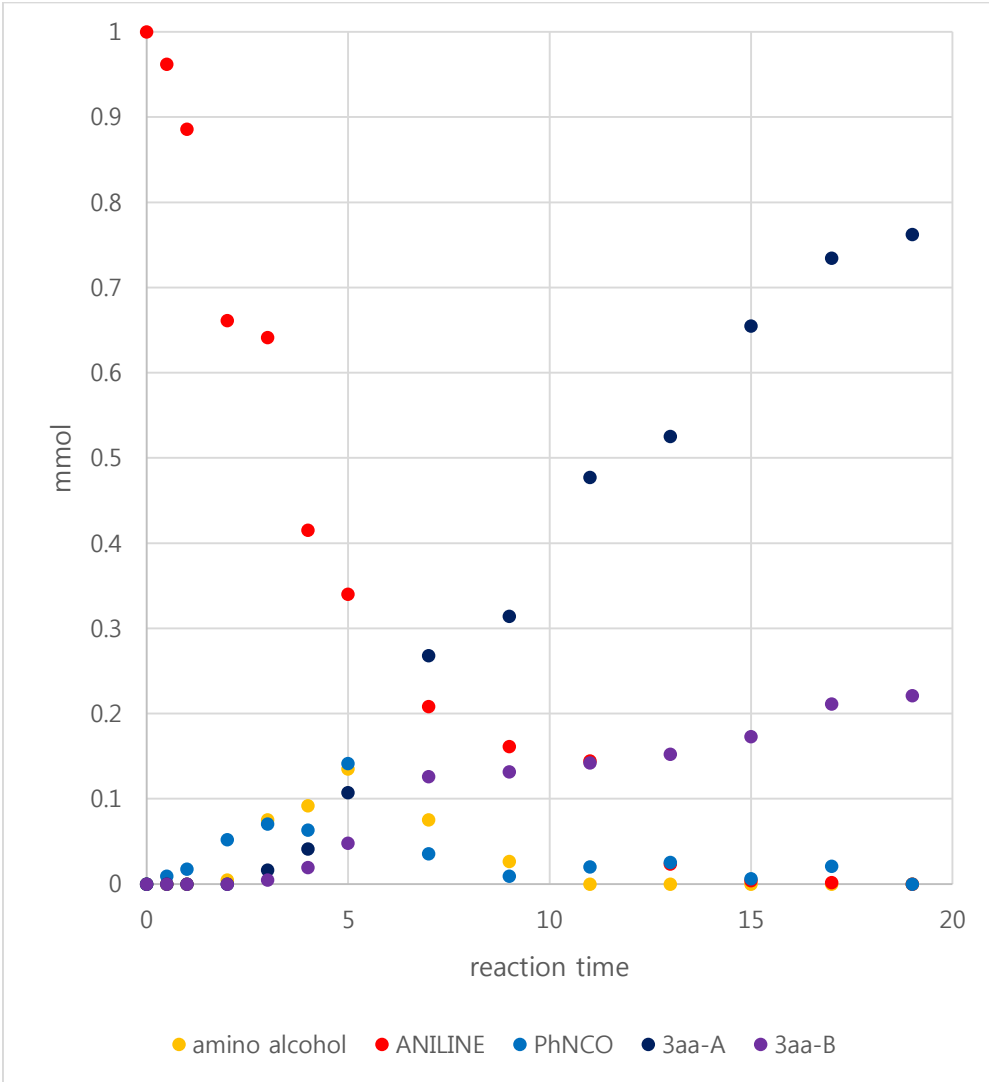
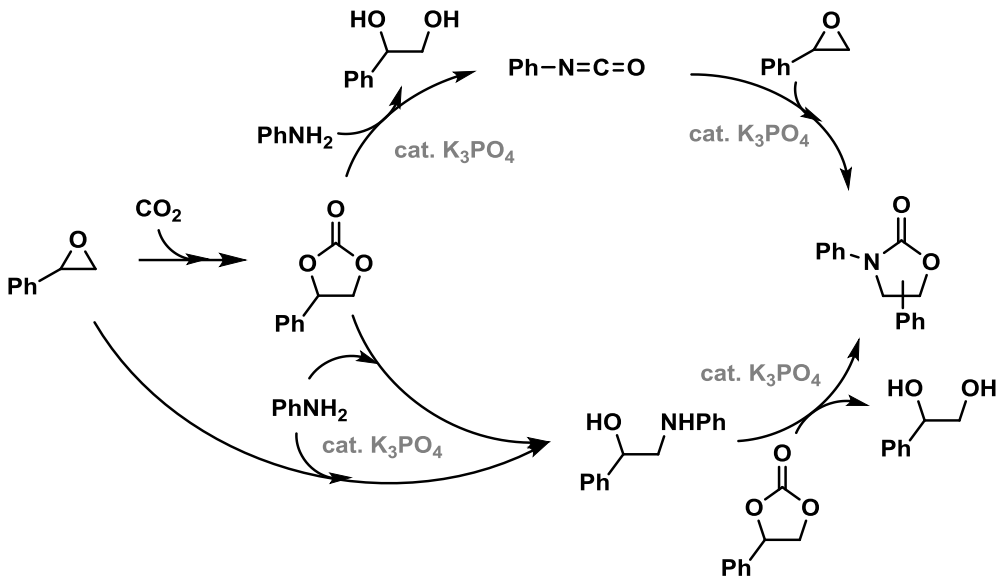


Figure 2. Expanded reaction profile for the oxazolidione synthesis from styrene oxide, aniline, and CO_2

Base on the above observation, we proposed phenyl isocyanate and amino alcohol as reaction intermediates under our reaction conditions. Gao et al.[15]proposed 1,2-amino alcohol as an intermediate, which reacted with another carbonate to produce oxazolidinone and diol. However, we envisaged two pathways for our reaction: a pathway based on the formation of phenyl isocyanate and a pathway based on 1,2-aminoalcohol. Based on our observations, we predicted that K_3PO_4 might be a suitable catalyst for our reactions, because both K^+ and PO_4^{3-} ions have an effect on some key-step reactions. Potassium is oxophilic, the central K^+ ion would form a strong coordinate bond with oxygen atoms in epoxide and cyclic carbonate, and the PO_4^{3-} counteranion is sufficiently basic.[28] A plausible reaction pathway was proposed (Scheme **2** for detailed discussion of the reaction mechanism, see experimental section).[12h,29]



Scheme 2. Plausible reaction mechanism

In conclusion, a potassium phosphate-catalyzed effective, scalable synthesis of oxazolidinones from amines, aryl epoxides, and carbon dioxide under mild conditions has been developed. These transformations employ CO_2 at atmospheric pressure and provide a streamlined access to useful heterocycle 3-aryl-2-oxazolidinones. The developed catalytic system is eco-friendly, requiring no transition metal catalyst or toxic reagents, such as phosgene or isocyanate.

3. Experimental Section

General

All solvents were obtained by passing through activated alumina columns of solvent purification systems from Glass Contour. *n*-Hexane and ethyl acetate were used without further purification. Reagents were purchased from Sigma-Aldrich, Alfa Aesar, Acros, and TCI and were used as received. Reactions were carried out in a flame -dried glassware equipped with a stirring bar and capped with a rubber septum under N_2 or CO_2, unless otherwise indicated. Elevated temperatures were maintained in thermostat-controlled oil baths. The TLC plate was carried out on 0.25 mm E. Merck silica gel plates (60F-254) visualized by UV-light (254 nm) and treatment with acidic *p*-anisaldehyde and $KMnO_4$ stain followed by gentle heating. Workup procedures were done in air. Flash chromatography was carried out on Merck 60 silica gel (230 – 400 mesh). IR spectra were measured on a Thermo Scientific Nicolet 6700 spectrometer. ^1H and ^{13}C NMR spectra were recorded with Varian spectrometer (400 MHz) spectrometer. ^1H NMR spectra were referenced to residual TMS (0 ppm) and reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, dd = doublet of doublets, m = multiplet). Chemical shifts of the ^{13}C NMR spectra were measured relative to $CDCl_3$ (77.16 ppm). Mass spectral data were obtained from the Korea Basic Science Institute (Daegu) on a Jeol JMS 700 high resolution mass spectrometer.

General Procedure for epoxidation of styrene derivatives

Reactions were performed in a flame-dried 100 mL Schlenk flask equipped with a stirring bar and a rubber septum. The flask was charged with *m*-chloroperbenzoic acid and dichloromethane (20 mL). The mixture was cooled to 0 ℃ and styrene derivative was slowly added. After 30 min, the reaction mixture was warmed to room temperature and allowed to overnight. Then the reaction mixture was quenched by addition of the sodium carbonate solution and then sodium thiosulfate solution. The reaction mixture was then extracted with dichloromethane and water. The organic layer was combined, dried over anhydrous $MgSO_4$, filtered, and concentrated under reduced pressures. The crude product was purified by flash chromatography on silica gel with *n*-hexane and ethyl acetate.

General Procedure for 2-Oxazolidiones

Reactions were performed in a tube schlenk equipped with a stirring bar and capped with a rubber cap and the followings were placed in the tube in order: 20 mol% of K_3PO_4 (43 mg, 0.2 mmol), 5 equiv. of styrene oxide (0.6 g, 5 mmol), 1 equiv. of aniline (93 μL, 1 mmol), and 2mL of DMF. While they were mixing together, the tube was charged with CO_2 by a balloon for 15 seconds. The mixture was stirred at 130 ºC for 19 h under CO_2 (using a balloon). The color of the reaction mixture changed from light yellow to dark brown. After the reaction, the mixture was concentrated under reduced pressures. Purification by flash chromatography on silica gel with *n*-hexane and ethyl acetate afforded oxazolidiones. The products were

characterized by ^{1}H NMR, ^{13}C NMR, IR, and HRMS, and their melting points were measured.

10 Gram-Scale Experiment

K_3PO_4 (20 mol%, 4.6 g), styrene oxide (540 mmol, 62 mL), aniline (108 mmol, 10.05 g), and DMF (100 mL) were place in a flame-dried two-necked 500 mL schlenk flask. Before the reaction flask was put to an oil bath, it was purged CO_2 for 30 seconds at room temperature. The reaction mixture was then heated at 130 ^{o}C for 19 h. To provide CO_2 smoothly and continually, the CO_2 balloon was recharged in every 3 h with a 18G needle. After the reaction went completion, the solvent was removed under reduced pressures. The crude product was purified by flash chromatography with hexane and ethyl acetate to afford products (total 93 % isolated yield).

Monitoring the synthesis of oxazolidinones

A. GC analysis

K_3PO_4 (43 mg, 0.2 mmol), styrene oxide 4 (0.6 g, 5 mmol), aniline (93 μL, 1 mmol), and DMF (2 mL) were placed in an oven-dried tube schlenk. Mesitylene (139 μL, 1 mmol) as an internal standard was added to the reaction mixture. The reaction mixture was stirred under carbon dioxide for 15 sec at room temperature. The reaction tube was heated at 130 ^{o}C. After 0 min, 30 min, 1 h, 2 h, 3 h, 4 h, 5 h, 7 h, 9 h, 11 h, 13 h, 15 h, 17 h and 19 h of reaction times, small portions of the reaction medium (about 10 μL) were diluted in dichloromethane for GC-analysis.

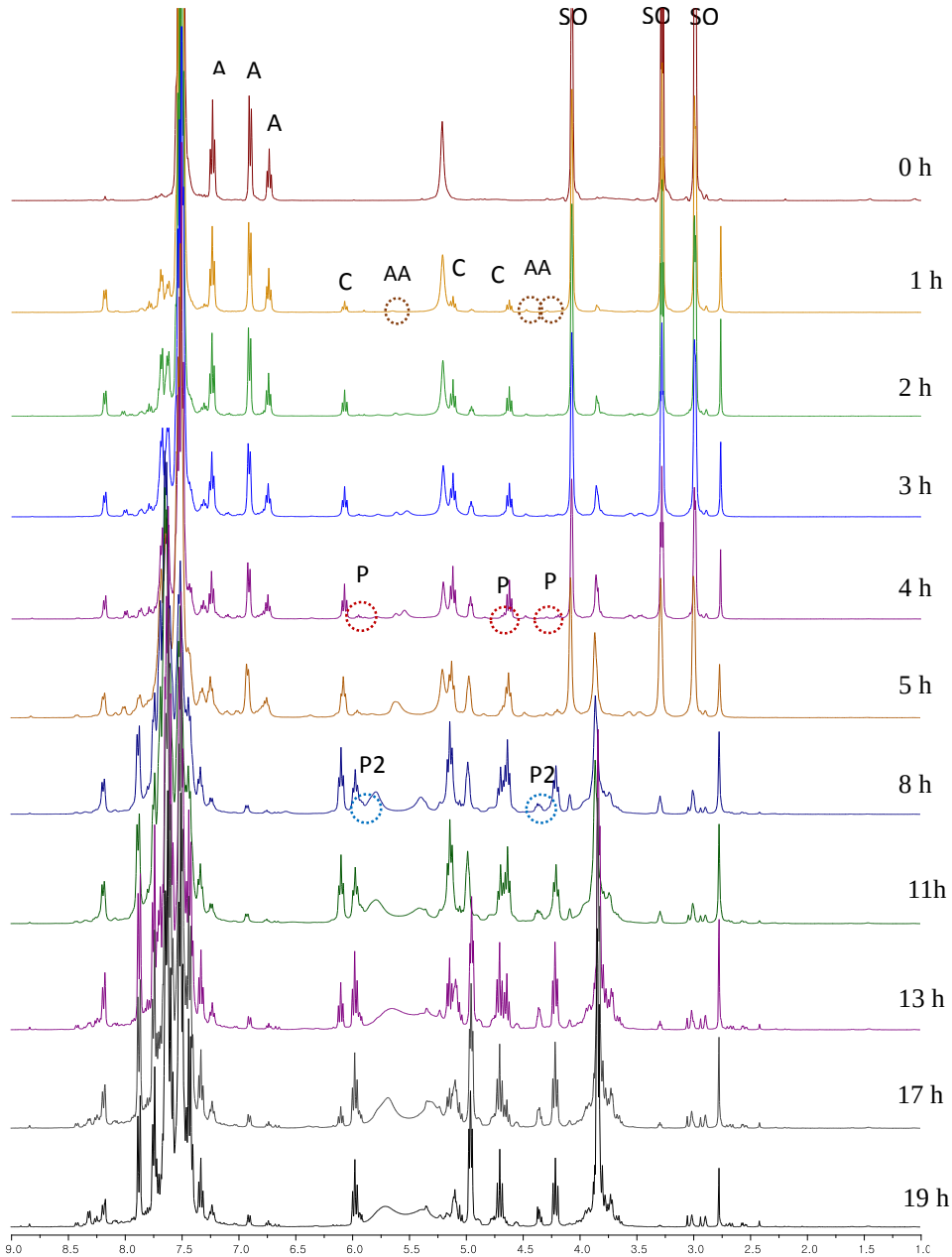
B. ^{1}H NMR spectroscopic investigation of reaction intermediates

Aniline (46 μL, 0.5 mmol), styrene oxide (286 μL, 2.5 mmol), and potassium phosphate (21 mg, 20 mol %) in d^7-DMF (1.0 g) was placed in an oven dried schlenk tube. The reaction mixture was heated to 130 ^{o}C in the presence of atmospheric CO_2. At the indicating time, ^{1}H NMR spectra were taken at room temperature after 0 h, 1 h, 2 h, 3 h, 4 h, 5 h ,8 h, 11 h, 13 h, 15 h, 17 h, and 19 h, respectively (Figures 3).

After 1 h, a small portion of styrene carbonate appeared. However, we could hardly see the formation of amino alcohol because a small amount of amino alcohol was generated. Further heating led to generate more styrene carbonate than amino alcohol, suggesting that styrene carbonate was rapidly generated. After 4h, 3aa-A was detected. The formation of amino alcohol was observed in the time range from 1 h to 5 h. After that, the peaks of amino alcohol were overlapped with other peaks so that we were not able to distinguish the characteristic peaks of amino alcohol. Product 3aa-B was detected after 8 h of reaction. However, two peaks of 3aa-A were overlapped: one of the peaks was overlapped with 3aa-A and the other with styrene carbonate. The amount of cyclic carbonate increased until 13 h of reaction time, then decreased. After 19 h, there is no styrene carbonate left. From this study, we could confirm the formation of phenyl isocyanate and amino alcohol as reaction intermediates. The information obtained from this study was somewhat similar to that obtained from the reaction-monitoring by GC-Mass.

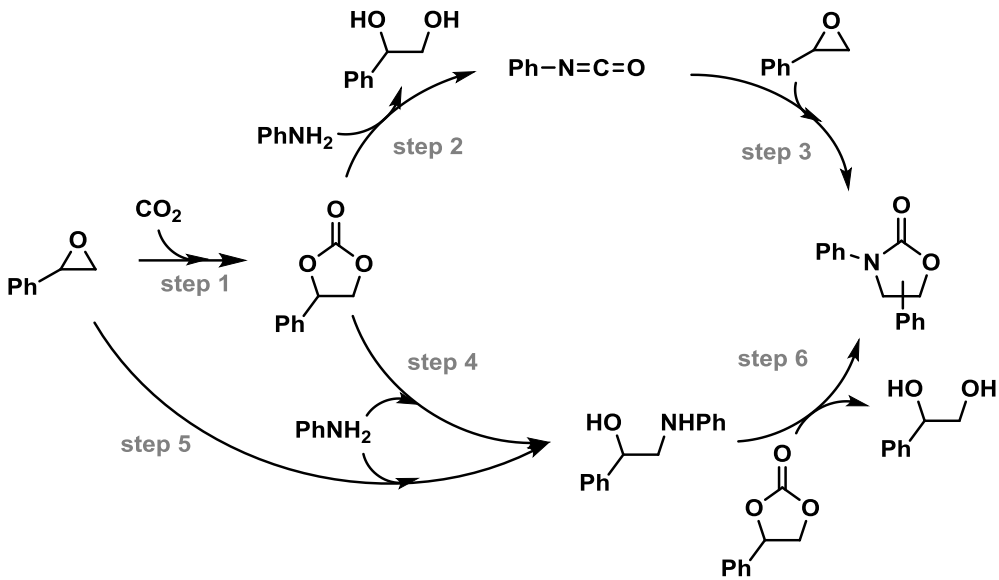
Figure 3 ^{1}H NMR spectra of the expanded reaction profile for the oxazolidione synthesis

(A: aniline, SO: styrene oxide, AA: amino alcohol, P: **3aa-A**, P2: **3aa-B**)



Discussion of the Reaction Mechanism

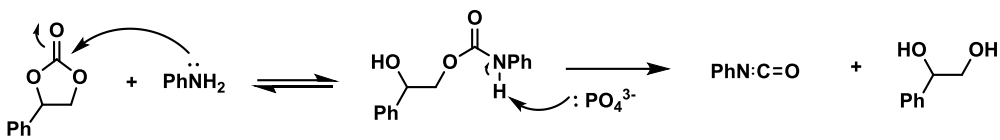
In the scheme **2**, we checked each step with or without K_3PO_4.



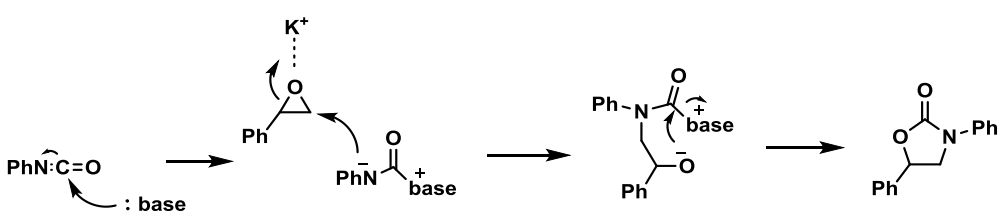
Step 1. Styrene oxide was reacted with carbon dioxide to generate styrene carbonate. In the presence or absence of K_3PO_4, the yield of styrene carbonate is 35% and 19 %, respectively. Potassium could activate styrene oxide by its oxophilicity.

Step 2. Styrene carbonate with aniline could generate phenyl isocyanate, a key intermediate. In the presence of K_3PO_4, the reaction went to the final product. In order to confirm the formation of phenyl isocyanate, a reaction was monitored by GC-MS. We found the formation of phenyl isocyanate after 30 min of a reaction time. However, without K_3PO_4, no reaction occurred.

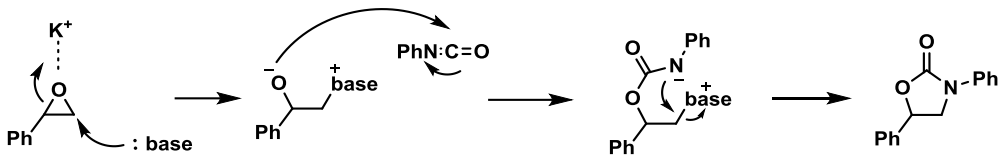
Aniline attacks the carbonyl carbon of styrene oxide to afford a carbamate. We assume that this is a reversible step. However, in the presence of K_3PO_4, the proton on the carbamate could be deprotonated by phosphate anion, leading to the formation of diol and phenyl isocyanate.



Step 3. A reaction of styrene oxide with phenyl isocyanate afforded the final product. This step was proven in equation 5, showing an overall 97 % yield. Without K_3PO_4, no reaction was observed. The reaction is a well-known reaction.[44] The reaction mechanism might be similar to that of previously reported cases. Thus, the potassium ion can coordinate to the epoxide forming adducts in which the epoxide ring is activated toward ring-opening. In the meantime, the phosphate reacts with phenyl isocyanate to activate. Nucleophilic attack of the potassium coordinated species on the carbonyl of the activated phenyl isocyanate leads to the product.



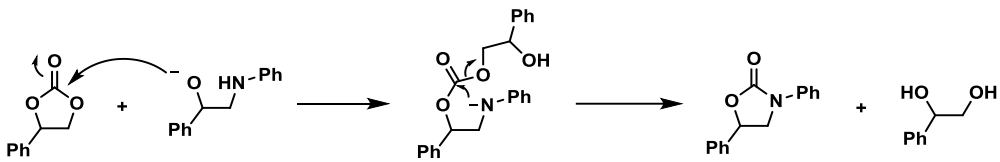
Alternatively, the following reaction scheme could be considered.



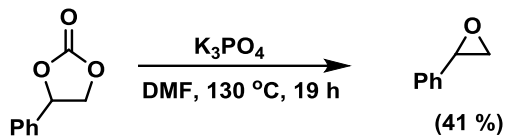
Step 4. A formation of amino alcohol from a reaction between styrene carbonate and aniline in the presence of a catalyst is a well-known reaction.[45]

Step 5. The reaction between styrene oxide and aniline in the presence of K_3PO_4 afforded 11% of amino alcohol (eq 6). Without K_3PO_4, no reaction occurred. So, we could identify the catalyst effect on the reaction even though the effect was not great. As already mentioned, a potassium ion can coordinate to the epoxide that the epoxide ring is activated toward ring-opening.

Step 6. In the presence of K_3PO_4, a quantitative yield of products was observed (shown in equation 7). However, without K_3PO_4, no reaction occurred. The reaction between amino alcohol and acyclic carbonate in the presence of a combination of HCO_3^- anion with potassium or imidazolium cation was published.[46] The reaction mechanism might be similar to that of the published paper: the PO_4^{3-} base acts as a nucleophile to activate the alcohol function to initiate transesterification reactions. The reaction might be followed by O→N acyl transfer migration, and the cyclization affords the final product.

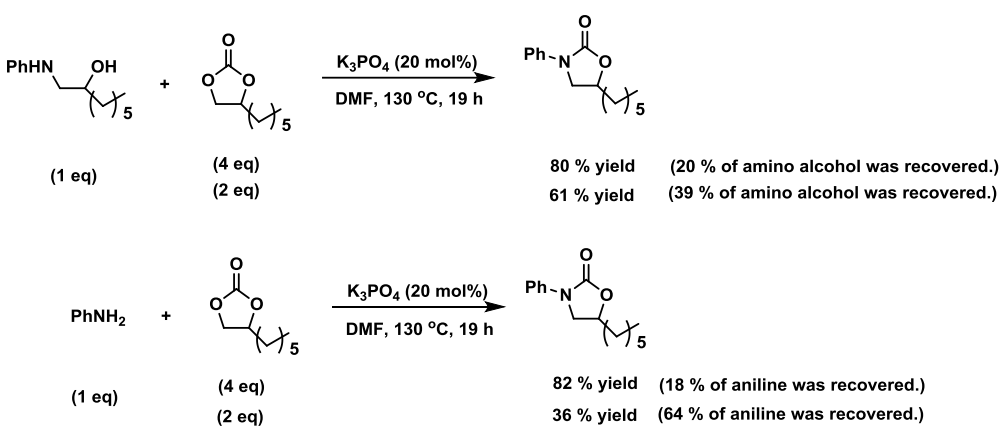


Thermal decomposition of styrene carbonate.



Styrene carbonate (0.16 g, 1 mmol) reacted with potassium phosphate (43 mg, 20 mol %) in 1 mL of DMF at 130 °C for 19 h. Styrene oxide was isolated in 41 % yield.

Reactions of aliphatic cyclic carbonate with amino alcohols and aniline



The yield of oxazolidinone was highly sensitive to the amount of cyclic carbonate used.

Characterization of product

3aa-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54 (d, *J* = 7.9 Hz, 2 H), 7.48 – 7.32 (m, 7 H), 7.13 (t, *J* = 7.4 Hz, 1 H), 5.67 – 5.59 (m, 1 H), 4.37 (t, *J* = 8.8 Hz, 1 H), 3.95 (dd, *J* = 8.7, 7.7 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.8, 138.2 (2), 129.2, 129.1, 125.8, 124.3, 118.4, 74.1, 52.8 ppm. HRMS (EI) calc. for [$C_{15}H_{13}NO_2$]: 239.0946, found: 239.0948; IR (neat): 1758 cm^{-1} (C=O); M.P.: 128 °C; white solid.

3aa-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36 – 7.27 (m, 2 H), 7.29 – 7.06 (m, 7 H), 6.96 (t, *J* = 7.4 Hz, 1 H), 5.29 (dd, *J* = 8.6, 6.1 Hz, 1 H), 4.65 (td, *J* = 8.7, 2.1 Hz, 1 H), 4.11 – 4.04 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.9, 138.2, 137.0, 129.3, 128.9, 128.8, 126.2, 124.6, 120.8, 69.8, 60.6 ppm. HRMS (EI) calc. for [$C_{15}H_{13}NO_2$]: 239.0946, found: 239.0944; IR (neat): 1757 cm^{-1} (C=O); M.P.: 128 °C; light yellow solid.

3ba-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.53 (d, *J* = 8.4 Hz, 2 H), 7.46 – 7.31 (m, 4 H), 7.18 – 7.04 (m, 3 H), 5.64 – 5.54 (m, 1 H), 4.41 – 4.30 (m, 1 H), 3.96 – 3.86 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.3, 161.9, 154.6, 138.1, 133.9, 129.2, 127.8, 127.7, 124.3, 118.4, 116.2, 116.0, 73.6, 52.7 ppm. HRMS (EI) calc. for [$C_{15}H_{12}FNO_2$]: 257.0852, found: 257.0855; IR (neat): 1759 cm^{-1} (C=O); M.P.: 110 °C; light yellow solid.

3ba-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34 (d, *J* = 8.4 Hz, 2 H), 7.25 (m, 4 H), 7.10 – 6.96 (m, 3 H), 5.37 (dd, *J* = 8.6, 6.2 Hz, 1 H), 4.75 (t, *J* = 8.7 Hz, 1 H), 4.15 (dd, *J* = 8.6, 6.1 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.0, 161.6, 155.8, 136.8, 134.0, 129.0, 128.2, 128.1, 124.9, 121.0, 116.6, 116.6, 116.4, 69.8, 60.1 ppm. HRMS (EI) calc. for [$C_{15}H_{12}FNO_2$]: 257.0852, found: 257.0852; IR (neat): 1758 cm^{-1} (C=O);

M.P.: 112 °C; white solid.

3ca-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.51 (d, *J* = 8.0 Hz, 2 H), 7.43 – 7.27 (m, 6 H), 7.13 (m, 1 H), 5.57 (t, *J* = 8.1 Hz, 1 H), 4.39 – 4.28 (m, 1 H), 3.92 – 3.82 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.5, 138.0, 136.6, 135.0, 129.2, 129.1, 127.1, 124.3, 118.3, 73.3, 52.5 ppm. HRMS (EI) calc. for [$C_{15}H_{12}ClNO_2$]: 273.0557, found: 273.0554; IR (neat): 1759 cm^{-1} (C=O); M.P.: 125 °C; white- yellowish solid.

3ca-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41 – 7.27 (m, 4 H), 7.24 (m, 4 H), 7.06 (t, *J* = 7.3 Hz, 1 H), 5.37 (dd, *J* = 8.6, 6.1 Hz, 1 H), 4.75 (t, *J* = 8.7 Hz, 1 H), 4.14 (dd, *J* = 8.6, 6.0 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.8, 136.8 (2), 134.8, 129.7, 129.1, 127.7, 125.0, 120.9, 69.6, 60.1ppm. HRMS (EI) calc. for [$C_{15}H_{12}ClNO_2$]: 273.0557, found: 273.0558; IR (neat): 1758 cm^{-1} (C=O); M.P.: 140 °C; white solid

3da-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.53 (m, 4 H), 7.36 (m, 2 H), 7.28 (d, *J* = 8.3 Hz, 2 H), 7.13 (t, *J* = 7.4 Hz, 1 H), 5.57 (t, *J* = 8.0 Hz, 1 H), 4.42 – 4.31 (m, 1 H), 3.91 – 3.86 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.5, 138.0, 137.2, 132.3, 129.2, 127.4, 124.4, 123.2, 118.4, 73.4, 52.6 ppm. HRMS (EI) calc. for [$C_{15}H_{12}BrNO_2$]:317.0051, found: 317.0053; IR (neat): 1759 cm^{-1} (C=O); M.P.: 144 °C; white solid.

3da-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 (d, *J* = 8.3 Hz, 2 H), 7.28 (d, *J* = 8.2 Hz, 2 H), 7.19 (t, *J* = 7.9 Hz, 2 H), 7.10 (d, *J* = 8.3 Hz, 2 H), 7.01 (t, *J* = 7.3 Hz, 1 H), 5.29 (dd, *J* = 8.6, 6.0 Hz, 1 H), 4.69 (t, *J* = 8.7 Hz, 1 H), 4.08 (dd, *J* = 8.6, 6.0 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.8, 137.4, 136.8, 132.6, 129.1, 128.0, 125.0, 122.9, 120.9, 69.5, 60.2 ppm. HRMS (EI) calc. for [$C_{15}H_{12}BrNO_2$]:317.0051,

found: 317.0053; IR (neat): 1758 cm^{-1} (C=O); M.P.: 144 °C; white solid.

3ea-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 (d, *J* = 8.3 Hz, 2 H), 7.28 (d, *J* = 8.2 Hz, 2 H), 7.19 (t, *J* = 7.9 Hz, 2 H), 7.10 (d, *J* = 8.3 Hz, 2 H), 7.01 (t, *J* = 7.3 Hz, 1 H), 5.29 (dd, *J* = 8.6, 6.0 Hz, 1 H), 4.69 (t, *J* = 8.7 Hz, 1 H), 4.08 (dd, *J* = 8.6, 6.0 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.8, 137.4, 136.8, 132.6, 129.1, 128.0, 125.0, 122.9, 120.9, 69.5, 60.2 ppm. HRMS (EI) calc. for [$C_{15}H_{12}BrNO_2$]:317.0051, found: 317.0053; IR (neat): 1758 cm^{-1} (C=O); M.P.: 144 °C; white solid.

3ea-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44 (d, *J* = 7.7 Hz, 1 H), 7.26 (d, *J* = 8.1 Hz, 2 H), 7.07 (m, 5 H), 6.90 (t, *J* = 7.2 Hz, 1 H), 5.72 – 5.60 (m, 1 H), 4.73 – 4.62 (m, 1 H), 4.03 – 3.91 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.6, 137.0, 136.9, 133.4, 130.0, 129.0, 128.3, 127.0, 124.3, 122.0, 119.5, 68.6, 59.2 ppm. HRMS (EI) calc. for [$C_{15}H_{12}BrNO_2$]:317.0051, found: 317.0052; IR (neat): 1761 cm^{-1} (C=O); M.P.: 123 °C; white solid.

3fa-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.52 (d, *J* = 7.9 Hz, 2 H), 7.41 (s, 1 H), 7.40 – 7.26 (m, 5 H), 7.15 (d, *J* = 7.4 Hz, 1 H), 5.60 (t, *J* = 8.1 Hz, 1 H), 4.42 – 4.33 (m, 1 H), 3.94 – 3.89 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.4, 140.2, 137.9, 135.0, 130.4, 129.2, 129.1, 125.8, 124.4, 123.7, 118.3, 73.2, 52.5 ppm. HRMS (EI) calc. for [$C_{15}H_{12}ClNO_2$]: 273.0557, found: 273.0553; IR (neat): 1759 cm^{-1} (C=O); M.P.: 100 °C; light yellow solid.

3fa-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36 (d, *J* = 8.1 Hz, 2 H), 7.26 (m, 5 H), 7.20 – 7.14 (m, 1 H), 7.07 (t, *J* = 7.1 Hz, 1 H), 5.35 (dd, *J* = 8.7, 5.8 Hz, 1 H), 4.76 (t, *J* = 8.7 Hz, 1 H), 4.21 – 4.11 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.7, 140.5, 136.8, 135.4, 130.9, 129.2, 129.1, 126.6, 125.0, 124.4, 120.8, 69.5, 60.2 ppm. HRMS

(EI) calc. for [$C_{15}H_{12}ClNO_2$]: 273.0557, found: 273.0558; IR (neat): 1761 cm^{-1} (C=O); M.P.: 102 ºC; white solid.

3ga-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.61 (d, *J* = 7.3 Hz, 1 H), 7.53 (d, *J* = 8.0 Hz, 2 H), 7.36 (m, 5 H), 7.12 (t, *J* = 7.4 Hz, 1 H), 5.91 (dd, *J* = 8.6, 6.9 Hz, 1 H), 4.61 – 4.51 (m, 1 H), 3.82 (dd, *J* = 8.9, 6.7 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.5, 138.0, 136.6, 131.1, 129.9, 129.8, 129.2, 127.6, 126.2, 124.3, 118.4, 71.2, 51.9 ppm. HRMS (EI) calc. for [$C_{15}H_{12}ClNO_2$]: 273.0557, found: 273.0559; IR (neat): 1760 cm^{-1} (C=O); M.P.: 123 ºC; white- yellowish solid.

3ga-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.51 – 7.37 (m, 3 H), 7.32 – 7.17 (m, 5 H), 7.06 (t, *J* = 7.4 Hz, 1 H), 5.88 – 5.80 (m, 1 H), 4.82 (m, 1 H), 4.15 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.6, 137.0, 135.6, 132.3, 130.2, 129.8, 129.1, 127.8, 127.0, 124.5, 119.7, 68.6, 57.1ppm. HRMS (EI) calc. for [$C_{15}H_{12}ClNO_2$]: 273.0557, found: 273.0559; IR (neat): 1761 cm^{-1} (C=O); M.P.: 138 ºC; white solid**.**

3ha-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54 (d, *J* = 8.0 Hz, 2 H), 7.37 (t, *J* = 7.9 Hz, 2 H), 7.30 (d, *J* = 8.0 Hz, 2 H), 7.23 (t, *J* = 6.4 Hz, 2 H), 7.13 (t, *J* = 7.3 Hz, 1 H), 5.58 (t, *J* = 8.1 Hz, 1 H), 4.37- 4.29 (m, 1 H), 3.94 (t, *J* = 8.2 Hz, 1 H), 2.36 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.9, 139.2, 138.3, 135.1, 129.8, 129.2, 125.9, 124.2, 118.4, 74.2, 52.8, 21.3 ppm. HRMS (EI) calc. for [$C_{16}H_{15}NO_2$]: 253.1103, found: 253.1101; IR (neat): 1755 cm^{-1} (C=O); M.P.: 118 ºC; white solid.

3ha-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38 (d, *J* = 8.0 Hz, 2 H), 7.23 (m, 2 H), 7.15 (m, 4 H), 7.04 (t, *J* = 7.4 Hz, 1 H), 5.34 (dd, *J* = 8.6, 6.1 Hz, 1 H), 4.72 (t, *J* = 8.7 Hz, 1 H), 4.15 (dd, *J* = 8.5, 6.1 Hz, 1 H), 2.29 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 156.0, 138.7, 137.1, 135.2, 130.0, 128.9, 126.2, 124.6, 120.9, 70.0, 60.5, 21.1ppm.

HRMS (EI) calc. for [$C_{16}H_{15}NO_2$]: 253.1103, found: 253.1103; IR (neat): 1755 cm^{-1} (C=O); M.P.: 120 °C; white solid.

3ia-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54 (d, *J* = 7.9 Hz, 2 H), 7.44 (d, *J* = 8.4 Hz, 2 H), 7.36 (m, 4 H), 7.14 (d, *J* = 7.4 Hz, 1 H), 5.60 (t, *J* = 8.1 Hz, 1 H), 4.38 – 4.31 (m, 1 H), 4.00 – 3.94 (m, 1 H), 1.32 (s, 9 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.9, 152.4, 138.3, 135.1, 129.2, 126.0, 125.6, 124.2, 118.4, 74.1, 52.7, 34.8, 31.4 ppm. HRMS (EI) calc. for [$C_{19}H_{21}NO_2$]: 295.1572, found: 295.1569; IR (neat): 1755 cm^{-1} (C=O); M.P.: 159 °C; white solid.

3ia-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 (d, *J* = 8.2 Hz, 2 H), 7.34 (d, *J* = 8.2 Hz, 2 H), 7.24 (m, 4 H), 7.05 (t, *J* = 7.3 Hz, 1 H), 5.35 (dd, *J* = 8.4, 6.1 Hz, 1 H), 4.78 – 4.68 (m, 1 H), 4.17 (dd, *J* = 8.4, 6.1 Hz, 1 H), 1.26 (s, 9 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.9, 137.3, 135.2, 129.0, 126.4, 126.0, 124.6, 120.9 (2), 70.0, 60.4, 34.7, 31.3 ppm. HRMS (EI) calc. for [$C_{19}H_{21}NO_2$]: 295.1572, found: 295.1573; IR (neat): 1755 cm^{-1} (C=O); M.P.: 162 °C; white solid.

3ja-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (d, *J* = 8.0 Hz, 2 H), 7.29 (t, *J* = 7.7 Hz, 2 H), 7.05 (t, *J* = 7.1 Hz, 1 H), 4.60 – 4.50 (m, 1 H), 4.00 (t, *J* = 8.5 Hz, 1 H), 3.57 (t, *J* = 7.8 Hz, 1 H), 1.78 (d, *J* = 8.0 Hz, 1 H), 1.70 – 1.61 (m, 1 H), 1.48 – 1.41 (m, 1 H), 1.38 – 1.22 (m, 7 H), 0.82 (d, *J* = 6.1 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.0, 138.5, 129.1, 124.0, 118.2, 73.2, 50.6, 35.1, 31.7, 29.0, 24.6, 22.6, 14.1 ppm. HRMS (EI) calc. for [$C_{15}H_{21}NO_2$]: 247.1572, found: 247.1575; IR (neat): 1739 cm^{-1} (C=O); M.P.: 68 °C; white solid.

3ka-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (d, *J* = 8.1 Hz, 2 H), 7.29 (t, *J* = 8.0 Hz, 2 H), 7.05 (t, *J* = 7.4 Hz, 1 H), 5.73 (ddt, *J* = 16.9, 10.2, 6.7 Hz, 1 H), 4.96 – 4.84 (m,

2 H), 4.59 – 4.51 (m, 1 H), 3.99 (t, *J* = 8.5 Hz, 1 H), 3.61 – 3.53 (m, 1 H), 1.98 (dd, *J* = 13.4, 6.5 Hz, 2 H), 1.83 – 1.74 (m, 1 H), 1.69 – 1.61 (m, 1 H), 1.47 – 1.26 (m, 8 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.0, 139.0, 138.5, 129.1, 124.0, 118.2, 114.4, 73.1, 50.6, 35.1, 33.8, 29.2, 28.9, 28.8, 24.6 ppm. HRMS (EI) calc. for [$C_{17}H_{23}NO_2$]: 273.1729, found: 273.1725; IR (neat): 1738 cm^{-1} (C=O); M.P.: 58 ^{o}C; yellowish solid.

3ab-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58 (d, *J* = 8.8 Hz, 2 H), 7.43 – 7.28 (m, 5 H), 7.25 (d, *J* = 8.8 Hz, 2 H), 5.55 (t, *J* = 8.1 Hz, 1 H), 4.30 – 4.20 (m, 1 H), 3.87 – 3.81 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.5, 138.0, 137.8, 129.3, 129.2, 125.7, 120.1, 87.6, 74.1, 52.5 ppm. HRMS (EI) calc. for [$C_{15}H_{12}INO_2$]: 364.9913, found: 364.9914; IR (neat): 1758 cm^{-1} (C=O); M.P.: 132 ^{o}C; white solid.

3ab-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.53 (d, *J* = 8.6 Hz, 2 H), 7.40 – 7.27 (m, 3 H), 7.25 (d, *J* = 7.6 Hz, 2 H), 7.16 (d, *J* = 8.6 Hz, 2 H), 5.33 (dd, *J* = 8.5, 6.1 Hz, 1 H), 4.76 (t, *J* = 8.7 Hz, 1 H), 4.18 (dd, *J* = 8.4, 6.2 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.5, 137.8, 137.7, 136.8, 129.4, 129.0, 126.1, 122.3, 88.3, 69.7, 60.3ppm. HRMS (EI) calc. for [$C_{15}H_{12}INO_2$]: 364.9913, found: 364.9917; IR (neat): 1758 cm^{-1} (C=O); M.P.: 132 ^{o}C; white solid.

3ac-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45 – 7.26 (m, 9 H), 5.54 (t, *J* = 8.1 Hz, 1 H), 4.30 – 4.20 (m, 1 H), 3.83 (t, *J* = 8.2 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.5, 137.8, 137.3, 132.1, 129.3, 129.1, 125.7, 119.8, 117.0, 74.1, 52.5 ppm. HRMS (EI) calc. for [$C_{15}H_{12}BrNO_2$]: 317.0051, found: 317.0051; IR (neat): 1758 cm^{-1} (C=O); M.P.:118 ^{o}C; white solid.

3ac-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.39 – 7.29 (m, 5 H), 7.30 – 7.23 (m, 4 H),

5.34 (dd, *J* = 8.7, 6.1 Hz, 1 H), 4.76 (t, *J* = 8.7 Hz, 1 H), 4.18 (dd, *J* = 8.6, 6.1 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.6, 137.6, 136.1, 131.8, 129.4, 129.0, 126.1, 122.1, 117.5, 69.7, 60.4 ppm. HRMS (EI) calc. for [$C_{15}H_{12}BrNO_2$]: 317.0051, found: 317.0049; IR (neat): 1759 cm^{-1} (C=O); M.P.: 136 ^{o}C; white solid.

3ad-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.48 (d, *J* = 8.9 Hz, 2 H), 7.39 (d, *J* = 9.1 Hz, 5 H), 7.30 (d, *J* = 8.9 Hz, 2 H), 5.61 (t, *J* = 8.1 Hz, 1 H), 4.37 – 4.27 (m, 1 H), 3.90 (t, *J* = 8.2 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.5, 137.8, 136.7, 129.3, 129.0 (2), 125.6, 119.3, 74.0, 52.5 ppm. HRMS (EI) calc. for [$C_{15}H_{12}ClNO_2$]:273.0557 found: 273.0553; IR (neat): 1758 cm^{-1} (C=O); M.P.: 126 ^{o}C; white- yellowish solid.

3ad-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43 – 7.29 (m, 5 H), 7.26 (d, *J* = 6.8 Hz, 2 H), 7.19 (d, *J* = 8.9 Hz, 2 H), 5.34 (dd, *J* = 8.7, 6.1 Hz, 1 H), 4.76 (t, *J* = 8.7 Hz, 1 H), 4.18 (dd, *J* = 8.6, 6.1 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.6, 137.7, 135.5, 129.8, 129.4, 128.9 (2), 126.1, 121.8, 69.7, 60.5 ppm. HRMS (EI) calc. for [$C_{15}H_{12}ClNO_2$]:273.0557 found: 273.0559; IR (neat): 1758 cm^{-1} (C=O); M.P.: 126 ^{o}C; white-yellowish solid.

3ae-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.64 (s, 1 H), 7.39 (d, *J* = 7.7 Hz, 1 H), 7.35 – 7.26 (m, 5 H), 7.19 – 7.06 (m, 2 H), 5.52 (t, *J* = 8.1 Hz, 1 H), 4.29 – 4.18 (m, 1 H), 3.80 (t, *J* = 8.2 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.3, 139.4, 137.7, 130.4, 129.2, 129.1, 127.0, 125.7, 122.8, 121.0, 116.6, 74.1, 52.4 ppm. HRMS (EI) calc. for [$C_{15}H_{12}BrNO_2$]:317.0051, found: 317.0050; IR (neat): 1755 cm^{-1} (C=O); M.P.: 110 ^{o}C; white solid.

3ae-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.57 (s, 1 H), 7.25 – 7.09 (m, 6 H), 7.06 – 6.99

(m, 1 H), 6.94 (t, *J* = 8.1 Hz, 1 H), 5.22 (dd, *J* = 8.6, 5.9 Hz, 1 H), 4.63 (t, *J* = 8.7 Hz, 1 H), 4.08 – 4.02 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.5, 138.4, 137.7, 130.1, 129.5, 129.0, 127.6, 126.2, 123.6, 122.6, 118.9, 69.9, 60.4 ppm. HRMS (EI) calc. for [$C_{15}H_{12}BrNO_2$]:317.0051, found: 317.0053; IR (neat): 1756 cm^{-1} (C=O); M.P.: 119 ^{o}C; white solid.

3af-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58 (d, *J* = 8.0 Hz, 1 H), 7.45 – 7.28 (m, 7 H), 7.19 – 7.13 (m, 1 H), 5.64 (t, *J* = 8.1 Hz, 1 H), 4.30 – 4.20 (m, 1 H), 3.85 (t, *J* = 8.1 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 156.2, 138.2, 136.2, 133.9, 130.0, 129.8, 129.1, 129.0, 128.8, 125.9, 122.6, 75.5, 54.6ppm. HRMS (EI) calc. for [$C_{15}H_{12}BrNO_2$]:317.0051, found: 317.0048; IR (neat): 1761 cm^{-1} (C=O); M.P.: 121 ^{o}C; white solid.

3af-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.57 (d, *J* = 7.8 Hz, 1 H), 7.31 (m, 5 H), 7.11 (m, 2 H), 6.98 (d, *J* = 7.5 Hz, 1 H), 5.37 (dd, *J* = 8.5, 6.8 Hz, 1 H), 4.92 - 4.78 (m, 1 H), 4.42 (dd, *J* = 8.6, 6.7 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 156.4, 137.5, 135.0, 133.7, 129.7, 129.2 (2), 128.3, 127.5, 125.9, 122.8, 70.4, 62.0 ppm. . HRMS (EI) calc. for [$C_{15}H_{12}BrNO_2$]:317.0051, found: 317.0049; IR (neat): 1760 cm^{-1} (C=O); M.P.: 119 ^{o}C; white solid.

3ag-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.23 (d, *J* = 7.5 Hz, 2 H), 7.72 (d, *J* = 7.6 Hz, 2 H), 7.52 – 7.34 (m, 5 H), 5.74 – 5.65 (m, 1 H), 4.45 (t, *J* = 8.9 Hz, 1 H), 4.05 – 3.97 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.1, 143.7, 143.5, 137.3, 129.6, 129.3, 125.7, 125.1, 117.6, 74.4, 52.5 ppm. HRMS (EI) calc. for [$C_{15}H_{12}N_2O_4$]: 284.0797, found: 284.0795; IR (neat): 1765 cm^{-1} (C=O); M.P.: 165 ^{o}C; light yellow solid.

3ah-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 – 7.26 (m, 7 H), 7.09 (d, *J* = 8.3 Hz, 2 H), 5.52 (dd, *J* = 8.6, 7.6 Hz, 1 H), 4.26 (t, *J* = 8.8 Hz, 1 H), 3.84 (dd, *J* = 8.9, 7.6 Hz, 1 H), 2.24 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.8, 138.3, 135.7, 133.9, 129.7, 129.1 (2), 125.7, 118.5, 74.1, 52.9, 20.8 ppm. HRMS (EI) calc. for [$C_{16}H_{15}NO_2$]: 253.1103, found: 253.1107; IR (neat): 1754 cm^{-1} (C=O); M.P.: 103 °C; white solid.

3ah-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38 – 7.21 (m, 7 H), 7.03 (d, *J* = 8.3 Hz, 2 H), 5.34 (dd, *J* = 8.6, 6.2 Hz, 1 H), 4.72 (t, *J* = 8.7 Hz, 1 H), 4.14 (dd, *J* = 8.5, 6.2 Hz, 1 H), 2.22 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 156.1, 138.3, 134.4 (2), 129.4, 129.3, 128.7, 126.3, 121.0, 69.7, 60.7, 20.7 ppm. HRMS (EI) calc. for [$C_{16}H_{15}NO_2$]: 253.1103, found: 253.1101; IR (neat): 1755 cm^{-1} (C=O); M.P.: 103 °C; yellow solid.

3ai-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.48 – 7.31 (m, 7 H), 6.89 (d, *J* = 8.9 Hz, 2 H), 5.58 (t, *J* = 8.1 Hz, 1 H), 4.36 – 4.25(m, 1 H), 3.88 (t, *J* = 8.2 Hz, 1 H), 3.77 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 156.4, 154.9, 138.2, 131.3, 129.0, 128.9, 125.6, 120.2, 114.2, 73.9, 55.4, 53.1 ppm. HRMS (EI) calc. for [$C_{16}H_{15}NO_3$]: 269.1052, found: 269.1055; IR (neat): 1754 cm^{-1} (C=O); M.P.: 114 °C; white solid.

3ai-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31 (m, 5 H), 7.23 (d, *J* = 9.0 Hz, 2 H), 6.76 (d, *J* = 8.9 Hz, 2 H), 5.34 – 5.25 (m, 1 H), 4.74 (t, *J* = 8.7 Hz, 1 H), 4.22 – 4.15 (m, 1 H), 3.70 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.0, 156.4, 138.3, 130.0, 129.4, 128.9, 126.6, 123.4, 114.3, 69.8, 61.4, 55.4 ppm. HRMS (EI) calc. for [$C_{16}H_{15}NO_3$]: 269.1052, found: 269.1052; IR (neat): 1754 cm^{-1} (C=O); M.P.: 109 °C; light yellow solid.

3aj–A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45 – 7.24 (m, 7 H), 7.10 (d, *J* = 8.6 Hz, 2 H), 5.52 (t, *J* = 8.1 Hz, 1 H), 4.30 – 4.22 (m, 1 H), 3.88 – 3.80 (m, 1 H), 2.54 – 2.47 (m, 2 H), 1.49 (m, 2 H), 1.26 (m, 2 H), 0.84 (t, *J* = 7.3 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.9, 139.0, 138.3, 135.8, 129.1, 129.0, 125.7, 118.4, 74.1, 52.9, 35.0, 33.7, 22.3, 14.0 ppm. HRMS (EI) calc. for [$C_{19}H_{21}NO_2$]: 295.1572, found: 295.1569; IR (neat): 1755 cm^{-1} (C=O); M.P.: 100 °C; white solid.

3aj–B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42 – 7.19 (m, 7 H), 7.04 (d, *J* = 8.2 Hz, 2 H), 5.34 (dd, *J* = 8.3, 6.3 Hz, 1 H), 4.74 (t, *J* = 8.7 Hz, 1 H), 4.17 (dd, *J* = 8.2, 6.3 Hz, 1 H), 2.49 (t, *J* = 7.7 Hz, 2 H), 1.49 (m, 2 H), 1.28 (m, 2 H), 0.87 (t, *J* = 7.3 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 156.2, 139.5, 138.5, 134.7, 129.4, 128.9, 128.8, 126.4, 121.0, 69.9, 60.9, 35.0, 33.5, 22.4, 14.0 ppm. HRMS (EI) calc. for [$C_{19}H_{21}NO_2$]: 295.1572, found: 295.1576; IR (neat): 1755 cm^{-1} (C=O); M.P.: 117 °C; light yellow solid.

3ak-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33 (m, 5 H), 7.09 (s, 2 H), 6.71 (s, 1 H), 5.51 (t, *J* = 8.0 Hz, 1 H), 4.31 – 4.21 (m, 1 H), 3.84 (t, *J* = 8.2 Hz, 1 H), 2.23 (s, 6 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.8, 138.9, 138.3, 138.1, 129.1 (2), 126.0, 125.7, 116.3, 74.0, 53.0, 21.6 ppm. HRMS (EI) calc. for [$C_{17}H_{17}NO_2$]: 267.1259, found: 267.1260; IR (neat): 1755 cm^{-1} (C=O); M.P.: 108 °C; light yellow solid.

3ak-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32 (m, 5 H), 6.98 (s, 2 H), 6.69 (s, 1 H), 5.34 (dd, *J* = 8.7, 6.0 Hz, 1 H), 4.76 – 4.69 (m, 1 H), 4.16 (dd, *J* = 8.6, 6.0 Hz, 1 H), 2.20 (s, 6 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 156.1, 138.6, 136.9, 129.4, 129.3, 128.8, 126.8, 126.4, 119.1, 69.9, 60.9, 21.5 ppm. HRMS (EI) calc. for [$C_{17}H_{17}NO_2$]: 267.1259, found: 267.1260; IR (neat): 1759 cm^{-1} (C=O); M.P.: 109 °C; light yellow

solid.

3al-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.50 (d, *J* = 9.0 Hz, 2 H), 7.47 – 7.36 (m, 5 H), 7.32 (t, *J* = 7.9 Hz, 2 H), 7.09 (d, *J* = 7.4 Hz, 1 H), 7.03 (d, *J* = 9.0 Hz, 2 H), 6.97 (d, *J* = 7.7 Hz, 2 H), 5.62 (t, *J* = 8.1 Hz, 1 H), 4.41 – 4.31 (m, 1 H), 3.96 – 3.91 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.4, 154.9, 153.6, 138.1, 133.7, 129.8, 129.2 129.1, 125.7, 123.3, 120.2, 119.8, 118.5, 74.1, 53.1 ppm. HRMS (EI) calc. for [$C_{21}H_{17}NO_3$]: 331.1208, found: 331.1206; IR (neat): 1754 cm^{-1} (C=O); M.P.: 118 °C; white solid.

3al-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.39 – 7.26 (m, 9 H), 7.06 (t, *J* = 7.4 Hz, 1 H), 6.92 (m, 2 H), 6.88 (m, 2 H), 5.32 (dd, *J* = 8.7, 6.3 Hz, 1 H), 4.77 (t, *J* = 8.7 Hz, 1 H), 4.20 (dd, *J* = 8.6, 6.2 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.0, 156.2, 154.3, 138.2, 132.3, 129.8, 129.5, 129.0, 126.5, 123.5, 123.0, 119.2, 118.9, 69.9, 61.2 ppm. HRMS (EI) calc. for [$C_{21}H_{17}NO_3$]: 331.1208, found: 331.1206; IR (neat): 1754 cm^{-1} (C=O); M.P.: 130 °C; light yellow solid.

3am-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93 – 7.81 (m, 3 H), 7.57 – 7.40 (m, 9 H), 5.83 (t, *J* = 8.0 Hz, 1 H), 4.46 – 4.38 (m, 1 H), 4.02 – 3.96 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 156.9, 138.4, 134.7, 133.8, 129.9, 129.1, 129.0, 128.8, 128.7, 127.1, 126.6, 125.6 (1), 124.6, 122.3, 75.2, 56.4 ppm. HRMS (EI) calc. for [$C_{19}H_{15}NO_2$]: 289.1103, found: 289.1100; IR (neat): 1758 cm^{-1} (C=O); M.P.: 150 °C; yellowish solid.

3am-B: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.97 (d, *J* = 8.4 Hz, 1 H), 7.82 (d, *J* = 8.1 Hz, 1 H), 7.72 (d, *J* = 8.3 Hz, 1 H), 7.57 (t, *J* = 7.6 Hz, 1 H), 7.48 (d, *J* = 7.2 Hz, 1 H), 7.30 – 7.22 (m, 6 H), 7.13 (s, 1 H), 5.38 (s, 1 H), 5.01 – 4.92 (m, 1 H), 4.55 – 4.49

(m, 1 H) ppm ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.2), 134.6, 130.1, 129.1 (2), 128.7 (2), 128.6, 127.3, 126.9, 126.7, 126.4, 126.3, 125.3, 122.5, 70.3, 63.5 ppm. HRMS (EI) calc. for [$C_{19}H_{15}NO_2$]: 289.1103, found: 289.1101; IR (neat): 1759 cm^{-1} (C=O); M.P.: 148 ^oC; yellow solid.

3an-A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44 – 7.22 (m, 10 H), 5.45 (t, *J* = 8.1 Hz, 1 H), 4.54 (d, *J* = 14.8 Hz, 1 H), 4.39 (d, *J* = 14.8 Hz, 1 H), 3.75 (m, 1 H), 3.32 – 3.26 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.0, 138.7, 135.7, 128.9(2), 128.2, 128.1, 125.6, 74.6, 51.6, 48.5 ppm. HRMS (EI) calc. for [$C_{16}H_{15}NO_2$]: 253.1103, found: 253.1103; IR (neat): 1753 cm^{-1} (C=O); M.P.: 80 ^oC; white solid.

3ao –A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.49 – 7.25 (m, 5 H), 5.46 (t, *J* = 8.1 Hz, 1 H), 3.92 – 3.86 (m, 1 H), 3.43 – 3.36 (m, 1 H), 3.35 – 3.21 (m, 2 H), 1.56 – 1.44 (m, 2 H), 1.37 – 1.12 (m, 10 H), 0.86 (t, *J* = 6.7 Hz, 3 H)ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.0, 139.0, 129.0, 128.8, 125.6, 74.4, 52.3, 44.3, 31.8, 29.3(2), 27.5, 26.7, 22.7, 14.2 ppm. HRMS (EI) calc. for [$C_{17}H_{25}NO_2$]: 275.1885, found: 275.1887; IR (neat): 1750 cm^{-1} (C=O); M.P.: 95 ^oC; yellow solid.

Chapter 2.

Base-catalyzed one-pot synthesis of unsymmetric fluorenes from aromatic ortho-dialdehydes and 1,3-dicarbonyl compounds

1. Introduction

The efficient and economic construction of complex molecules from readily available and simple starting materials is highly desirable.[33] In this regard, domino reactions are among the most effective methods for achieving improved synthetic efficiency, because these processes generate high levels of diversity, giving rise to complex structures[34] by simultaneous formations of many chemical bonds from simple substrates in a one-pot reaction.[35] Substrates that are suitable for domino reactions must contain multiple functional groups that take part in chemical transformations, or the requisite functional groups must be generated *in situ* from previous reactions. Therefore, judicious choice of the substrate is a prerequisite for successful synthesis of target molecules by domino reactions that have proved powerful in the synthesis of various carbocycles and heterocycles.[36]

Fluorenes and their substituted derivatives have found widespread applications in advanced materials[37] owing to the unique electronic and photonic properties associated with these compounds. They are also widely utilized in organic synthesis and peptide chemistry.[38] Thus, facile access to fluorenes having a number of functional groups will be of high value to both organic synthesis and materials chemistry. In spite of the importance of these molecules, only a limited number of methods for their preparing have been developed, and these methods generally require harsh reaction conditions or complicated multistep procedures.[39] The synthesis of unsymmetrically substituted fluorenes is particularly challenge.[40] Transition metal-catalyzed reactions have emerged as an efficient approach for the synthesis of fluorenes.[41] However, general strategies for the regioselective synthesis of poly-substituted fluorenes are uncommon.

The strategy presented herein provides a new route to polycyclic aromatic hydrocarbons possessing a fluorenyl skeleton without the need for a transition metal catalyst which might contaminate the desired product. Besides starting with simple substrate could provide highly efficient synthetic challenges. Our study demonstrated that the base-catalyzed one-pot domino reaction of aromatic *ortho*-dialdehydes with 1,3-dicarbonyl compounds readily furnishes the 6,5,6-tricyclic ring system with multiple substituents. This was based upon the recognition of aromatic 1,2-dialdehydes as a synthon of 1,4-biselectrophile and envisioned it to serve as a key building block for the construction of fluorene skeletons. [36,42] Thus, a strategy was formulated by the condensation of dialdehyde with 1,3-dicarbonyl compounds, where the four carbonyl groups could engage in multiple aldol-type processes.

Herein we wish to report the first base-catayzed one-pot domino raction of dialdehyde with 1,3-dicarbonyl, which gives unsymmetric fluorene dereivatives. This highly efficient and scalable synthetic method provides a modular route for the assembly of an interesting class of structurally diverse polycyclic aromatic hydrocarbons, including fluorenes, benzo[*b*]fluorenes, and 13*H*-indeno[1,2-*b*]anthracene.

2. Result and Discussion

In practice, our studies started with evaluating the reaction of phthalaldehyde with acetylacetone in the presence of a base (Table **6**). Upon treating phthalaldehyde (**1a**) pentane-2,4-dione (**2a,** 4equiv.) in the presence of 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) in DMF at 120 ^{o}C for 4 h, a mixture of **3aa**, **3'aa**, **4aa**, and **5aa** was formed in overall 81% yield. GC-MS analysis indicated that the mixture consisted of **3aa**, **3'aa**, **4aa**, and **5aa** in 39%, 1%, 34%, and 7% yields, respectively (entry 1), the structures of which were confirmed by X-ray diffraction study of the corresponding single crystals (**Fig 4-7**).

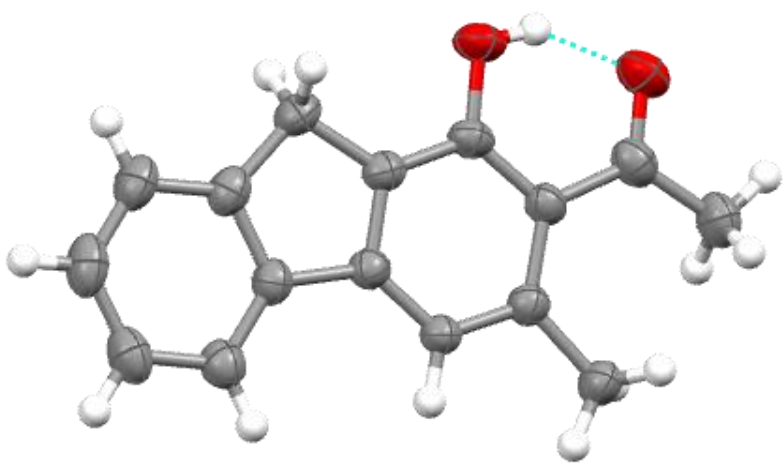


Figure 4. X-ray structure of **3aa**

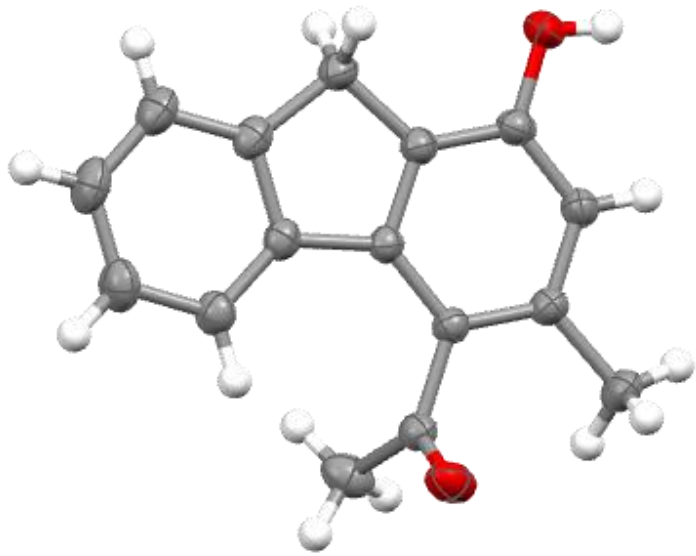


Figure 5. X-ray structure of **3'aa**

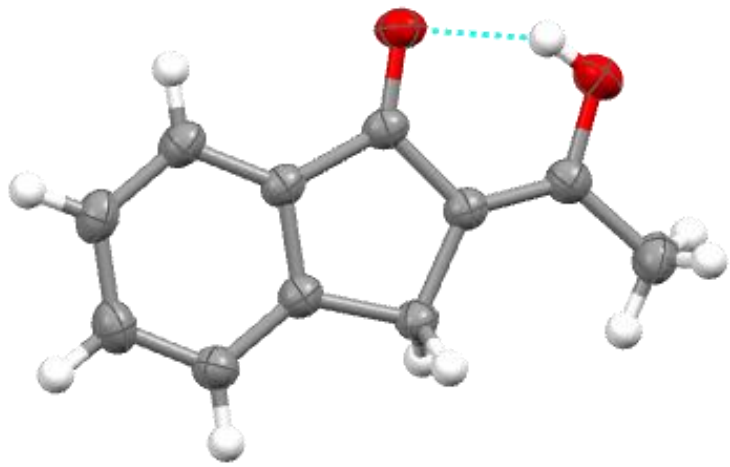


Figure 6. X-ray structure of **4aa**

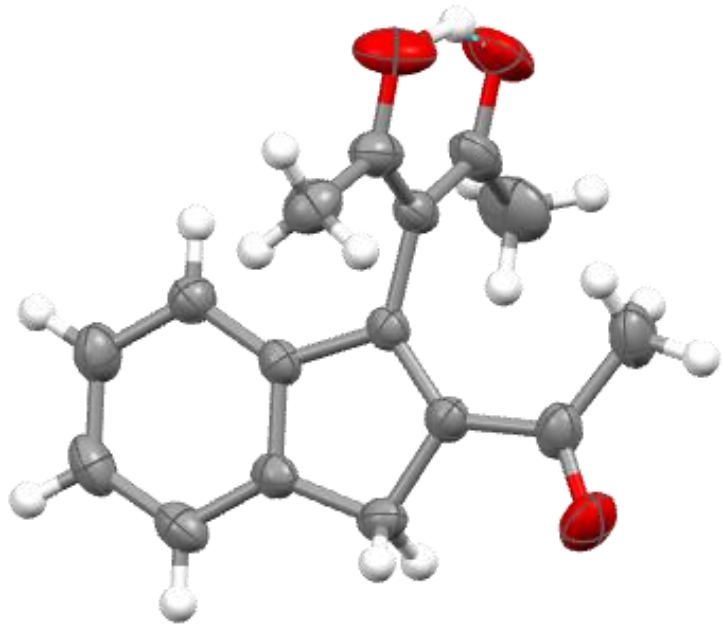
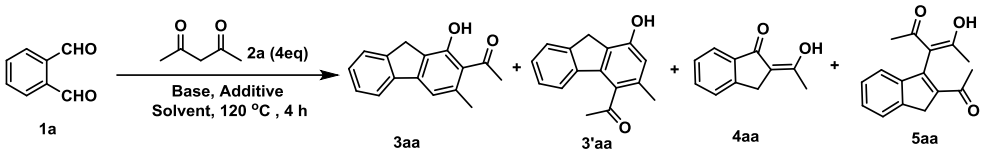


Figure 7. X-ray structure of **5aa**

Compounds **3aa** and **3'aa**, a 1:2 adduct of **1a** and **2a** with loss of two carbon atoms, are isomers possessing an unsymmetrically substituted fluorene skeleton. Compound **4aa** is a 2,3-dihydro-1*H*-inden-1-one derivative that was first synthesized over a century ago by condensing phthalaldehyde with acetone in aqueous potassium hydroxide, [43] while its crystal structure was reported in 1993. [44] It appeared that **4aa** was derived from a 1:1 reaction of **1a** and **2a** accompanying deacetylation. Compound **5aa** proved to be a 1*H*-indene derivative, formed by the reaction of **1a** with 2 equivalents of **2a** which resulted in monocyclization.

The reaction conditions were optimized to obtain the maximum yield of the major product **3aa**. Bases such as K_2HPO_4, NaOH, NaOMe, K_2CO_3, and $NaHCO_3$ were screened (entries 1-6). Among these bases, the highest yield was obtained with K_2HPO_4. Using K_2HPO_4 as a base, additives such as NaBr, KBr, CuBr, LiCl, NaCl, and NaI were next screened (entries 7-12). The use of NaBr as an additive produced the highest yield (64 % by GC) and, interestingly, no formation of **4aa** was detected. Solvent screening was also performed and the highest yield was achieved in DMF (entries 7, 13-15). It was notable that the reaction temperature not only affected the yield (entries 7, 16, and 17) but also the ratio of **1a** to **2a** (entries 7, 18-20). When the ratio of **1a**:**2a** was increased to 1:10, the highest yield (70% by GC) was observed. Finally, the optimal yield (75% by GC) was obtained after 12 h of reaction time (entry 21), although the isolated yield (64%) was lower due to sublimation of **3aa**. Therefore, the optimized reaction conditions were as follows: 1 equiv **1a**, 10 equiv **2a**, 15 mol% K_2HPO_4, 10 mol% of NaBr, DMF, 120 ^oC, 12 h of reaction time.

Table 6. Optimization of reaction conditions [a]

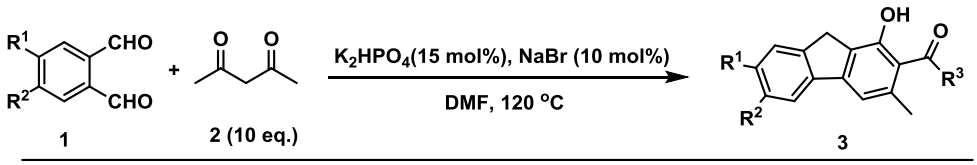


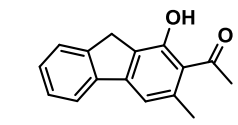
Entry	Solvent	Base	Additive	GC yield (%)			
				3aa	**3'aa**	**4aa**	**5aa**
1	DMF	DBU	-	39	1	34	7
2	DMF	K_2HPO_4	-	56	12	10	9
3	DMF	NaOH	-	47	6	22	8
4	DMF	NaOMe	-	53	9	9	10
5	DMF	K_2CO_3	-	47	6	18	6
6	DMF	$NaHCO_3$	-	50	8	12	8
7	DMF	K_2HPO_4	NaBr	64	9	0	13
8	DMF	K_2HPO_4	KBr	54	9	9	10
9	DMF	K_2HPO_4	CuBr	58	8	0	10
10	DMF	K_2HPO_4	LiCl	45	8	0	15
11	DMF	K_2HPO_4	NaCl	59	7	6	9
12	DMF	K_2HPO_4	NaI	56	6	2	12
13	DMSO	K_2HPO_4	NaBr	49	5	11	7
14	NMP	K_2HPO_4	NaBr	59	3	1	12
15	PhMe	K_2HPO_4	NaBr	43	7	0	36
16[b]	DMF	K_2HPO_4	NaBr	62	8	2	10
17[c]	DMF	K_2HPO_4	NaBr	50	7	3	9
18[d]	DMF	K_2HPO_4	NaBr	63	8	0	14
19[e]	DMF	K_2HPO_4	NaBr	70	8	0	16
20[f]	DMF	K_2HPO_4	NaBr	54	5	3	10
21[e,g]	DMF	K_2HPO_4	NaBr	75(64[h])	8 (7[h])	0	11 (9[h])

GC yields were determined using mesitylene as an internal standard. [a] Reaction conditions: additive (10 mol%), base (15 mol%), **2a** (4 equiv), **1a** (0.5 mmol), and solvent (1 mL) were reacted at 120 °C under nitrogen. [b]At 100 °C. [c]At 140 °C. Reactants ratio (**1a** : **2a**): [d]1:6, [e]1:10, and [f]1:3. [g]12 h. [h] Isolated yield

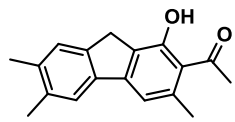
Having optimized the reaction conditions, the base-catalyzed one-pot domino reaction was applied to a range of aromatic *ortho*-dialdehydes **1** was first explored in the reaction with **2a** (Table **7**). Generally, the dialdehyde substrates having electron-donating groups gave higher yields than those having electron-withdrawing groups. The reaction forms a contrast to a related acid-catalysed process that forms fluorenone skeletons in low yield (11-20 %) from the reaction of acetylacetone with benzaldehydes containing an electron donating substituent at a *meta* position. [45] 4,5-Dimethyl- and dimethoxy-substituted aromatic *ortho*-dialdehydes participated well in the reaction to afford high yields of fluorene products (76% and 80% for **3ba** and **3ca**, respectively). In a case of 4,5-dichlorophthalaldehyde (**1l**), the corresponding product was obtained in 55% yield. The reaction of unsymmetrically substituted substrates, 4-bromo- (**1n**), 4-methoxy- (**1j**), and 4-methyl-phthalaldehyde (**1i**), yielded a 1:1 mixture of two inseparable isomers (**3na**, **3ja**, and **3ia** in 55 - 83% yields). A heterocyclic substrate, 2,3-thiophenealdehyde (**1h**), also underwent the reaction albeit giving the product (**3ha**) in 25% yield. The base-catalyzed tandem cyclization reaction could be extended to the synthesis of benzo[*b*]fluorenes and indenoanthracene. The reactions of naphthyl dialdehydes, **1d**, **1e**, and **1f**, afforded benzo[*b*]fluorenes (**3da**, **3ea**, and **3fa**) in 88% and 91%, and 87% yields, respectively. 13*H*-Indeno[1,2-*b*]anthracene **3ga** was isolated in 71% yield from the reaction of anthracenyl substrate **1g** with **2a**. The reaction of **1m** with **2a** generated a doubly indene-fused 3,3'-bi-9*H*-fluorene derivative (**3ma**) in 40% yield as a single isomer. Thus, using the developed reaction, indene-fused polycyclic aromatic hydrocarbons, i.e., unsymmetrically polysubstituted fluorene, benzo[*b*]fluorene, and 13*H*-indeno[1,2-*b*]anthracene, [46] were easily obtained from simple starting materials.

Table 7. Synthesis of various unsymmetric fluorenes [a]

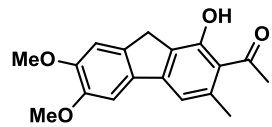




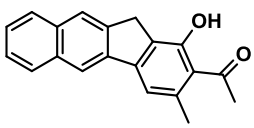
3aa, 75[b] (64) %



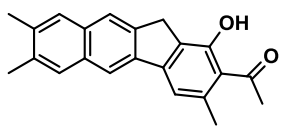
3ba, 76 %



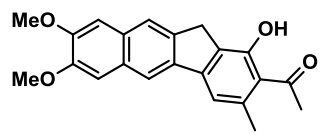
3ca, 80 %



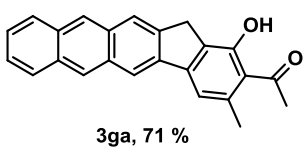
3da, 88 %



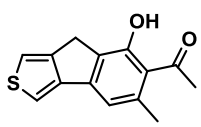
3ea, 91 %



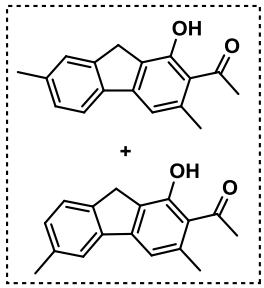
3fa, 87 %



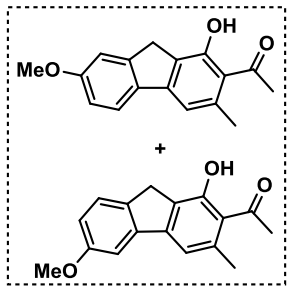
3ga, 71 %



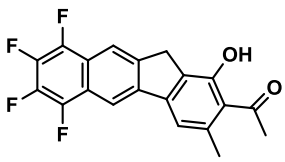
3ha[c], 25 %



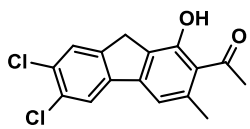
3ia, 78[b] (63) %
(1 : 1 mixture)



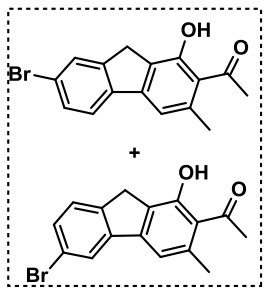
3ja, 83 %
(1 : 1 mixture)



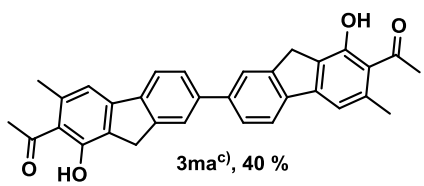
3ka[c),d)], 50 %



3la[c], 55 %



3na[c], 55 %
(1 : 1 mixture)



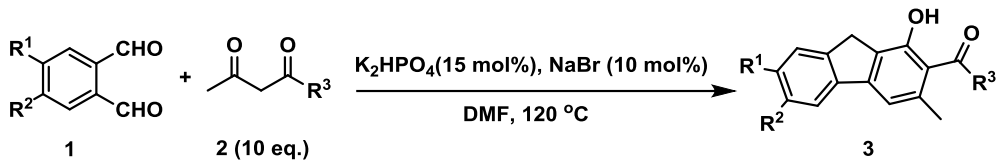
3ma[c], 40 %

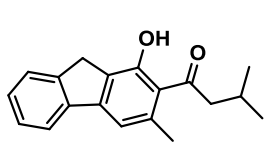
[a] Isolated yield. [b] NMR yield determined by using 1,3,5-trimethylbenzene as an internal standard. [c] For 24 h.

The scope of 1,3-dicarbonyl compounds (**2b-2f**) was investigated in the reaction with dialdehydes (**1a, 1b**, **and 1c**) (Table **8**).

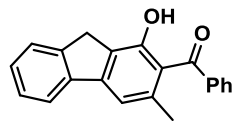
The product and yield of the reaction were highly sensitive to the 1,3-dicarbonyl compounds used. The reaction of **1a** with 2,4-dioxo-6-methylheptane (**2b**) afforded **3ab** in 61% yield. In the same way, a reaction of **1c** with **2b** gave **3cb** in 66% yield. However, other 1,3-dicarbonyl compounds **2c-2f** produced relatively lower yields (32–39%) of isomeric products, fluorenyl **3'**. In these cases, increasing the amount of 1,3-dicarbonyl substrates gave no improvement. Nonetheless, it was noteworthy that the selectivity of the final product **3** vs. **3'** is highly dependent upon the substituent of 1,3-dicarbonyl substrates **2**.

Table 8. Synthesis of various unsymmetric fluorenes [a]

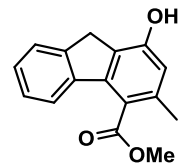




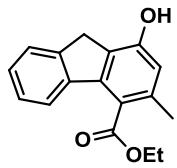
3ab, 61 %



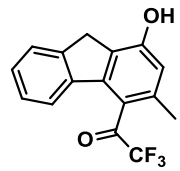
3ac[b], 36%



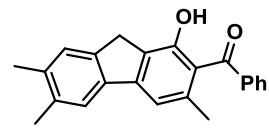
3'ad, 38 %



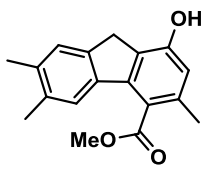
3'ae, 37 %



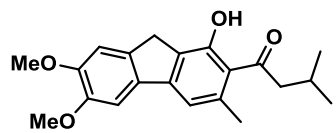
3'af, 39 %



3bc, 32 %



3'bd, 38 %

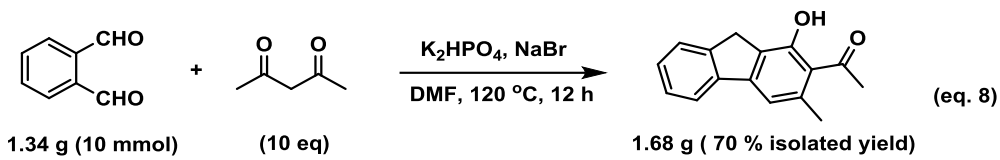


3cb, 66 %

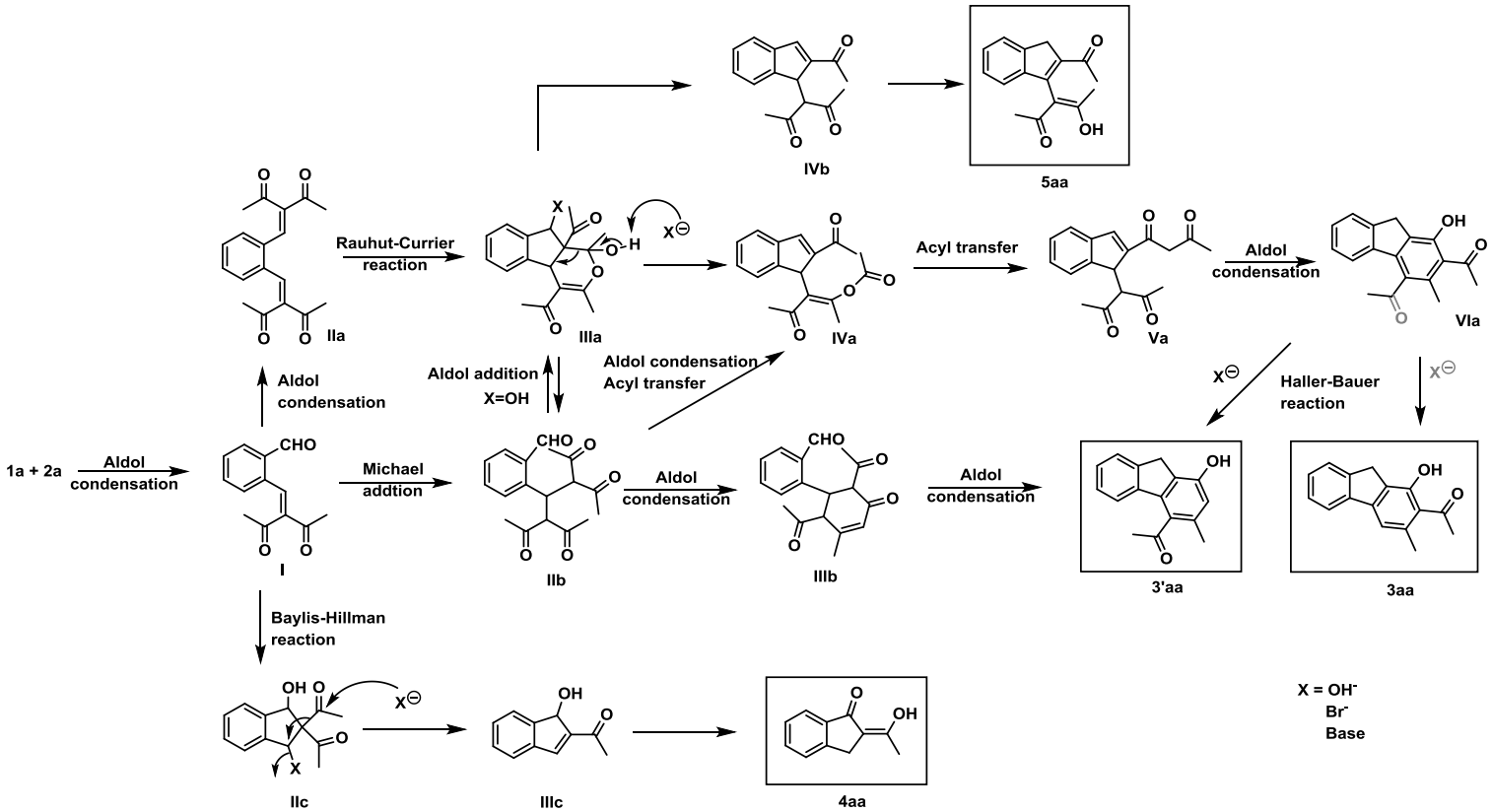
R^3, b =isobutyl
c = Ph
d = OMe
e = OEt
f = CF_3

[a] Isolated yield. [b] For 4 h

In addition, the reaction could be conducted on a gram scale (1.34g of **1a**; 1.68 g of **3aa**) (eq 8).



On the basis of the results described above, a plausible mechanism for the reaction of phthalaldehyde (**1a**) with pentane-2,4-dione (**2a**) in the presence of a base is illustrated in Scheme **3**. The cascade of bond-forming processes is initiated with the aldol condensation of **1a** and **2a** that affords intermediate **I**. While intermediate **I** may undergo an additional adol condensation to give **IIa**, it can also enter into a Michael addition or Baylis-Hillman-type pathway to provide **IIb** and **IIc**, respectively. The intermediate **IIa** undergoes a Rauhut-Currier reaction to form **IIIa**, which is then converted to **5aa** via **IVb** by deacylation. It is well noted that a structure similar to **IIIa** has been observed in a related reaction under acidic conditions.[44] The intermediate **IVa** generated by a ring-cleavage of **IIIa** undergoes sequential acyl transfer, intramolecular aldol condensation, and Haller-Bauer reactions to give fluorenes **3aa** and **3'aa**. Alternatively, **3aa** and **3'aa** may also be derived from the intermediate **IIb** via the intermediates **IIb** and **IIIb**. The intermediate **IIc** undergoes deacylation and then isomerization to give **4aa**.



Scheme 3 Proposed mechanism

In conclusion, an efficient base-catalyzed method for the synthesis of fluorenes from aromatic *ortho*-dialdehydes and 1,3-dicarbonyl compounds was demonstrated for the first time. The one-pot tandem domino reactions without the need for a transition metal catalyst afford a 5,6-bicyclic ring system of fluorenes with multiple substituents. The current protocol can be extended to the preparation of polycyclic fluorene systems such as benzo[*b*]fluorenes and 13*H*-indeno[1,2-*b*]anthracene. Thus, the method described herein is a highly efficient protocol for the construction of valuable unsymmetrically substituted fluorenes that are not easily assembled by other synthetic means. This process is highly efficient and scalable, offering a modular route for the assembly of an interesting class of structurally diverse polycyclic aromatic hydrocarbons, including fluorenes, benzo[*b*]fluorenes, and 13*H*-indeno[1,2-*b*]anthracene.

3. Experimental Section

General

All solvents were obtained by passing through activated alumina columns of solvent purification systems from Glass Contour. n-Hexanes and ethyl acetate were used without further purification. Reagents were purchased from Sigma-Aldrich, Alfa Aesar, Acros, and TCI and were used as received. Reactions were carried out in a flame -dried glassware equipped with a stirring bar and capped with a rubber septum under N_2, unless otherwise indicated. Elevated temperatures were maintained in thermostat-controlled oil baths. The TLC plate was carried out on 0.25 mm E. Merck silica gel plates (60F-254) visualized by UV-light (254 nm) and treatment with acidic *p*-anisaldehyde and $KMnO_4$ stain followed by gentle heating. Workup procedures were done in air. Flash chromatography was carried out on Merck 60 silica gel (230 – 400 mesh). IR spectra were measured on a Thermo Scientific Nicolet 6700 spectrometer. ^1H and ^{13}C NMR spectra were recorded with Bruker (300 MHz) and Varian spectrometer (400 MHz) spectrometer. ^1H NMR spectra were referenced to residual TMS (0 ppm) and reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, dd = doublet of doublets, td = triplet of doublets, qd = quertet of doublets, br s = broad singlet, m = multiplet). Chemical shifts of the ^{13}C NMR spectra were measured relative to $CDCl_3$ (77.16 ppm), DMSO (39.52 ppm). Mass spectral data were obtained from the Korea Basic Science Institute (Daegu) on a Jeol JMS 700 high resolution mass spectrometer.

General Procedures for dicarbaldehydes

General Procedure for the Reduction of Dicarboxylic Acids

Reactions were performed in a flame-dried 100 mL two-neck Schlenk fask equipped with a stirring bar and a rubber septum. The flask was charged with dicarboxylic acid (5 mmol) and THF (15 mL). The mixture was cooled to 0 ℃ and BH_3•THF (3 equiv for dicaboxylic acid) was slowly added. After the addition of BH_3•THF was completed, the reaction mixture was warmed to room temperature and allowed to react for 24 h. Then the reaction mixture was cooled to 0 ℃ and quenched by addition of the mixture of THF : H_2O (1:1, 30 mL). Solid K_2CO_3 was added to separate an aqueous layer from an organic layer. The reaction mixture was then extracted with THF. The organic layer was combined, dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The crude product was used in the next step without further purification (a quantitative yield).

General Procedure for the Swern Oxidation

A 100-mL flame-dried, three-necked schlenk flask equipped with a stir bar and a rubber septum was charged with 10 mL of methylene dichloride and oxalyl chloride (2.2 equiv for diol), and the resulting solution was cooled to -78 ℃. A solution of DMSO (3.4 equiv for diol) in methylene dichloride (2 mL) was added to the flask via a dropping funnel. The resulting mixture was stirred for 10 min after the addition of DMSO was completed. A solution of diol (2 mmol) in methylene dichloride (6 mL) was then slowly added to the reaction mixture. The resulting mixture was stirred

at -78 ℃ for 2 h. Then, TEA (18 equiv) was added. The mixture was stirred at -78 ℃ for 10 min, warmed to r.t. and stirred for additional 30 min. The reaction mixture was quenched with 20 mL of cold water and extracted with methylene dichloride. The organic layers were combined and dried over $MgSO_4$, filtered, and concentrated by a rotary evaporation. The crude product was purified by a flash chromatography with hexane and ethyl acetate to give a dialdehyde product.

General procedure for the synthesis of unsymmetric fluorenes

In the glove box, NaBr (10 mol%), K_2HPO_4 (15 mol%), pentane-2,4-dione (5 mmol), *ortho*-dialdehyde derivatives (0.5 mmol), and DMF (1 mL) were place in an oven dried 4 mL vial with a screw cap. The vial was taken out and stirred at 120 ℃ for 12 h. All volatiles were removed under vacuum. The reaction mixture was then purified under flash chromatography to afford the corresponding products.

Gram-scale experiment

NaBr (10 mol%, 0.12g), K_2HPO_4 (15 mol%, 0.26 g), pentane-2,4-dione (100 mmol, 10 mL), *ortho*-dialdehydes (10 mmol, 1.34 g), and DMF (20 mL) were place in a flame-dried two-necked 100mL schlenk flask. The reaction mixture was then heated at 120 ^oC for 12 h. After the reaction went completion, the solvent was removed under reduced pressure. The crude product was purified by flash chromatography with hexane and ethyl acetate (1.68 g, 70 % isolated yield).

X-ray Analysis

The crystal structure has been deposited at the Cambridge Crystallographic Data Centre (CCDC 1060431, 1060280, 1060281, 1060366). The data can be obtained free of charge via the Internet at www.ccdc.cam.ac.uk/data_request/cif.

Table 9. Crystal data and structure data, data collection and refinement.

Compound reference	**3aa**	**4aa**	**5aa**	**3'aa**
Chemical formula	$C_{16}H_{14}O_2$	$C_{11}H_{10}O_2$	$C_{16}H_{16}O_3$	$C_{16}H_{14}O_2$
Formula Mass	238.27	174.19	256.29	238.27
Crystal system	Monoclinic	Monoclinic	Orthorhombic	Monoclinic
a/Å	7.4657 (6)	7.2131 (3)	12.4618 (6)	12.4989 (5)
b/Å	23.2921 (18)	15.8857 (8)	15.2084 (8)	14.9009 (5)
c/Å	7.0317 (6)	7.9348 (4) Å	7.1595 (3)	13.1104 (5)
α/°	90.00	90.00	90.00	90.00
β/°	105.206 (2)	107.6924 (16)	90.00	98.624(2)
γ/°	90.00	90.00	90.00	90.00
Unit cell volume/Å ^{3}	1179.95 (17)	866.21 (7)	1356.90 (11)	2414.14(16)
Temperature/K	200	193	223	223
Space group	$P2_1/c$	$P2_1/n$	$Pca2_1$	$C2/c$
Z	4	4	4	8
Radiation type	Mo $K\alpha$	Cu $K\alpha$	Mo $K\alpha$	Mo $K\alpha$
Absorption coefficient, μ/mm^{-1}	0.09	0.74	0.09	0.09
No. of reflections measured	8498	11503	31751	33588
No. of independent reflections	2916	1717	2666	3012
Rint	0.035	0.068	0.219	0.051
$R[F^2 > 2\sigma(F^2)]$	0.058	0.058	0.049	0.0495
$wR(F^2)$	0.223	0.170	0.131	0.147
Goodness of fit on F2 (S)	1.12	1.10	1.04	1.04
CCDC number	CCDC 1060431	CCDC 1060280	CCDC 1060281	CCDC 1060366

Characterization of unsymmetric fluorenes

3aa: ^{1}H NMR (400 MHz, $CDCl_3$) δ 12.95 (s, 1 H), 7.78 – 7.72 (m, 1 H), 7.58 (dd, *J* = 5.7, 2.8 Hz, 1 H), 7.42 – 7.34 (m, 2 H), 7.16 (s, 1 H), 3.85 (s, 2 H), 2.69 (s, 6 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.0, 159.9, 148.2, 145.3, 140.6, 139.6, 128.5, 128.3, 126.9, 125.4, 120.9, 119.9, 115.2, 34.2, 33.6, 25.4 ppm. HRMS (EI) calc. for [$C_{16}H_{14}O_2$]: 238.0994, found: 238.0995; IR (neat): 3456 cm^{-1} (OH), 1711cm^{-1} (C=O); M.P.: 136 °C; light yellow solid.

3ba: ^{1}H NMR (400 MHz, $CDCl_3$) δ 12.98 (s, 1 H), 7.53 (s, 1 H), 7.36 (s, 1 H), 7.12 (s, 1 H), 3.79 (s, 2 H), 2.69 (s, 6 H), 2.36 (s, 3H), 2.35 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.9, 159.9, 148.6, 143.1, 139.6, 138.5, 137.3, 135.2, 128.4, 126.5, 121.9, 119.6, 115.0, 33.8, 33.5, 25.4, 20.4, 20.2 ppm. HRMS (EI) calc. for [$C_{18}H_{18}O_2$]: 266.1307, found: 266.1308; IR (neat): 3456m^{-1} (OH), 1727m^{-1} (C=O); M.P.: 197 °C; light yellow solid.

3ca: ^{1}H NMR (400 MHz, $CDCl_3$) δ 12.87 (s, 1 H), 7.79 (s, 1 H), 7.64 (s, 1 H), 7.09 (s, 1 H), 3.81 (s, 2 H), 2.71 (s, 6 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.2, 159.8, 145.9, 144.6, 140.7, 140.0, 132.1, 131.3, 128.9, 127.3, 122.5, 120.5, 115.2, 34.0, 33.6, 25.3 ppm. HRMS (EI) calc. for [$C_{16}H_{12}Cl_2O_2$]: 306.0214, found: 306.0214; IR (neat): 3457 cm^{-1} (OH), 1711cm^{-1} (C=O); M.P.: 220 °C; yellow solid.

3da: (1:1 mixture): ^{1}H NMR (400 MHz, $CDCl_3$) δ 12.98 (s, 1 H), 12.94 (s, 1 H), 7.63 (d, *J* = 7.8 Hz, 1 H), 7.56 (s, 1 H), 7.46 (d, *J* = 7.7 Hz, 1 H), 7.39 (s, 1 H), 7.21 – 7.16 (m, 2 H), 7.13 (d, *J* = 8.1 Hz, 2 H), 3.81 (s, 4 H), 2.69 (s, 6 H), 2.68 (s, 6 H), 2.45 (s, 3 H), 2.44 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.0, 205.9, 159.9(2), 148.4, 148.3, 145.6, 142.4, 140.8, 139.6, 139.5, 138.5, 138.0, 136.5, 129.3, 128.9, 128.2, 127.8, 126.1, 125.1, 121.5, 120.7, 119.9, 119.7, 115.1, 115.0, 34.0, 33.9, 33.6(2),

25.4(2), 21.8, 21.6 ppm. HRMS (EI) calc. for [$C_{17}H_{16}O_2$]: 252.1150, found: 252.1149; IR (neat): 3455 cm^{-1} (OH), 1716cm^{-1} (C=O); M.P.: 140 °C; light yellow solid.

3ia: ^{1}H NMR (400 MHz, $CDCl_3$) δ 12.90 (s, 1 H), 7.36 (s, 1 H), 7.12 (s, 1 H), 7.03 (s, 1 H), 3.69 (s, 2 H), 2.70 (s, 3 H), 2.68 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.9, 160.3, 146.9(2), 143.0, 139.7, 133.4, 119.9, 116.3, 116.0, 114.2, 33.6, 28.9, 25.3 ppm. HRMS (EI) calc. for [$C_{14}H_{12}O_2S$]: 244.0558, found: 244.0557; IR (neat): 3454m^{-1} (OH), 1708 cm^{-1} (C=O); M.P.: 130 °C; yellow solid.

3ac: ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.71 (s, 1 H), 7.73 – 7.69 (m, 1 H), 7.65 – 7.60 (m, 2 H), 7.56 – 7.47 (m, 2 H), 7.38 (dd, *J* = 11.5, 4.2 Hz, 2 H), 7.34 – 7.29 (m, 2 H), 7.13 (s, 1 H), 3.85 (s, 2 H), 1.99 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.8, 156.0, 147.4, 144.7, 140.7, 140.6, 138.7, 132.5, 128.8, 128.6, 127.9, 127.4, 126.8, 125.3, 120.9, 120.6, 114.7, 34.0, 23.3 ppm. HRMS (EI) calc. for [$C_{21}H_{16}O_2$]: 300.1150, found: 300.1146; IR (neat): 3447 cm^{-1} (OH), 1739cm^{-1} (C=O); M.P.: 148 °C; yellow solid.

3'ad: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.57 – 7.53 (m, 1 H), 7.51 – 7.47 (m, 1 H), 7.35 – 7.27 (m, 2 H), 6.55 (s, 1 H), 5.55 (bs, 1 H), 4.03 (s, 3 H), 3.70 (s, 2 H), 2.32 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.8, 152.6, 143.6, 140.3 139.7, 136.0, 127.1, 126.7, 126.6, 125.0, 121.6, 120.4, 115.2, 52.2, 33.0, 19.3 ppm. HRMS (EI) calc. for [$C_{16}H_{14}O_3$]: 254.0943, found: 254.0940; IR (neat): 3454 cm^{-1} (OH), 1724 cm^{-1} (C=O); M.P.:138 °C; yellow solid.

3bc: ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.90 (s, 1 H), 7.69 (d, *J* = 7.2 Hz, 2 H), 7.55 (d, *J* = 5.7 Hz, 2 H), 7.47 (d, *J* = 7.7 Hz, 2 H), 7.38 (s, 1 H), 7.14 (s, 1 H), 3.85 (s, 2 H), 2.37 (s, 3 H), 2.36 (s, 3 H), 2.05 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 202.0, 156.3, 148.0, 142.7, 141.0, 138.9, 138.7, 137.0, 135.3, 132.6, 128.9, 128.7, 127.4,

126.5, 121.8, 120.6, 114.6, 33.7, 23.5, 20.4, 20.2 ppm. HRMS (EI) calc. for [$C_{23}H_{20}O_2$]: 282.1256, found: 282.1254; IR (neat): 3451 cm^{-1} (OH), 1723 cm^{-1} (C=O); M.P.:176 ^oC; orange solid.

3'bd: ^1H NMR (300 MHz, $CDCl_3$) δ 7.23 (s, 2 H), 6.49 (s, 1 H), 4.96 (s, 1 H), 3.95 (s, 3 H), 3.62 (s, 2 H), 2.28 (s, 3 H), 2.25 (s, 6 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.7, 152.6, 141.5, 141.0, 137.8, 136.2, 136.1, 135.0, 131.2, 126.5, 126.2, 123.0, 114.8, 52.2, 32.7, 20.5, 20.2, 19.5 ppm. HRMS (EI) calc. for [$C_{18}H_{18}O_3$]: 282.1256, found: 282.1254; IR (neat): 3459 cm^{-1} (OH), 1711cm^{-1} (C=O); M.P.:186 ^oC; yellow solid.

3'ae: ^1H NMR (400 MHz, $CDCl_3$) δ 7.53 (d, *J* = 7.2 Hz, 1 H), 7.40 (d, *J* = 6.3 Hz, 1 H), 7.27 – 7.20 (m, 2 H), 6.45 (s, 1 H), 5.41 (s, 1 H), 4.45 (qd, *J* = 7.1, 1.8 Hz, 2 H), 3.61 (s, 2 H), 2.26 (s, 3 H), 1.36 (td, *J* = 7.2, 1.9 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.6, 152.7, 143.8, 140.3, 139.9, 136.0, 127.2, 126.8(2), 125.2, 121.9, 121.0, 115.4, 61.6, 33.1, 19.4, 14.3 ppm. HRMS (EI) calc. for [$C_{17}H_{16}O_3$]: 268.1099, found: 268.1098; IR (neat): 3448 cm^{-1} (OH), 1713cm^{-1} (C=O); M.P.: 132 ^oC; yellow solid.

3'af: ^1H NMR (400 MHz, $CDCl_3$) δ 7.41 (dd, *J* = 9.0, 3.4 Hz, 1 H), 7.38 – 7.33 (m, 1 H), 7.27 – 7.22 (m, 2 H), 6.87 (s, 1 H), 6.74 (bs, 1 H), 3.56 (s, 2 H), 2.64 (s, 3 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ 206.6, 152.5, 143.6, 139.4, 138.6, 133.6, 128.1, 127.5, 127.3, 126.5, 126.1, 125.5, 122.2, 111.73 (q, *J* = 4.5 Hz), 33.5, 33.0 ppm. HRMS (EI) calc. for [$C_{16}H_{11}F_3O_2$]: 292.0711, found: 292.0710; IR (neat): 3458 cm^{-1} (OH), 1706cm^{-1} (C=O);. M.P.: 113 ^oC; light yellow solid.

3ab: ^1H NMR (400 MHz, $CDCl_3$) δ 11.90 (d, *J* = 2.2 Hz, 1 H), 7.74 – 7.68 (m, 1 H), 7.52 (d, *J* = 6.3 Hz, 1 H), 7.33 – 7.27 (m, 2 H), 7.08 (d, *J* = 1.5 Hz, 1 H), 3.80 (s, 2

H), 2.83 (d, *J* = 7.2 Hz, 2 H), 2.64 (d, *J* = 2.2 Hz, 3 H), 1.71 (m, 1 H), 0.85 (d, *J* = 2.1 Hz, 3 H), 0.83 (d, *J* = 2.1 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.4, 158.3, 147.6, 145.1, 143.1, 140.8, 128.4, 128.2, 126.9, 125.4, 120.9, 120.6, 115.1, 45.9, 34.3, 32.5, 31.6, 22.6 ppm. HRMS (EI) calc. for [$C_{19}H_{20}O_2$]: 280.1463, found: 280.1462; IR (neat): 3455 cm^{-1} (OH), 1710cm^{-1} (C=O); M.P.: 116 °C; yellow solid.

3ea: ^{1}H NMR (400 MHz, $CDCl_3$) δ 12.97 (s, 1 H), 8.20 (s, 1 H), 8.00 (s, 1 H), 7.97 – 7.90 (m, 1 H), 7.87 (d, *J* = 4.9 Hz, 1 H), 7.52 – 7.46 (m, 2 H), 7.32 (s, 1 H), 4.03 (s, 2 H), 2.74 (s, 3 H), 2.72 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.0, 160.1, 147.5, 142.2, 139.7, 139.5, 133.9, 132.8, 129.5, 128.5, 128.0, 126.2, 125.7, 123.8, 120.5, 119.6, 115.6, 33.6(2), 25.4 ppm. HRMS (EI) calc. for [$C_{20}H_{16}O_2$]: 288.1150, found: 288.1148; IR (neat): 3457 cm^{-1} (OH), 1708cm^{-1} (C=O); M.P.: 213 °C; light yellow solid.

3ga: ^{1}H NMR (400 MHz, $CDCl_3$) δ 12.98 (s, 1 H), 8.52 (s, 1 H), 8.44 (s, 1 H), 8.36 (s, 1 H), 8.13 (s, 1 H), 8.05 – 7.99 (m, 2 H), 7.47 (dd, *J* = 6.6, 3.2 Hz, 2 H), 7.37 (s, 1 H), 4.10 (s, 2 H), 2.77 (s, 3 H), 2.74 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.0, 160.2, 147.2, 141.4, 139.7, 139.6, 132.0, 131.7, 131.3, 129.7, 128.2(2), 128.0, 127.0, 126.1, 125.6, 125.4, 123.6, 120.7, 119.6, 115.7, 33.6, 33.4, 25.4 ppm. HRMS (EI) calc. for [$C_{24}H_{18}O_2$]: 338.1307, found: 338.1305; IR (neat): 3461 cm^{-1} (OH), 1726cm^{-1} (C=O); M.P.:283 °C; light yellow solid.

3fa: ^{1}H NMR (300 MHz, $CDCl_3$) δ 12.97 (s, 1 H), 8.09 (s, 1 H), 7.88 (s, 1 H), 7.69 (s, 1 H), 7.62 (s, 1 H), 7.30 (s, 1 H), 4.01 (s, 2 H , 2.75 (s, 3 H), 2.72 (s, 3 H), 2.45 (s, 6 H) ppm. ^{1}H NMR (400 MHz, DMSO) δ 10.05 (bs, 1 H), 8.19 (s, 1 H), 7.92 (s, 1 H), 7.72 (s, 1 H), 7.68 (s, 1 H), 7.39 (s, 1 H), 3.96 (s, 2 H), 2.52 (d, *J* = 1.4 Hz, 3 H), 2.40 (s, 6 H), 2.29 (s, 3 H) ppm. ^{13}C NMR (100 MHz, DMSO) δ 205.1, 151.3,

143.0, 140.3, 138.8, 135.1, 134.8(2), 131.8, 131.3, 128.7, 127.4, 127.3, 127.1, 122.4, 117.4, 114.0, 33.5, 32.3, 19.8(2), 19.7 ppm. HRMS (EI) calc. for [$C_{22}H_{20}O_2$]: 316.1463, found:316.1462; IR (neat): 3454 cm^{-1} (OH), 1726 cm^{-1} (C=O); Dec. Temp.: 311 ^oC; light yellow solid.

3ha: ^1H NMR (400 MHz, $CDCl_3$) δ 12.94 (s, 1 H), 12.90 (s, 1 H), 7.95 (s, 1 H), 7.85 – 7.72 (m, 2 H), 7.67 – 7.55 (m, 3 H), 7.21 (d, *J* = 5.3 Hz, 1 H), 7.14 (d, *J* = 5.3 Hz, 1 H), 3.88 (s, 2 H), 3.85 (s, 2 H), 2.67 (s, 6 H), 2.66 (s, 6 H) ppm. ^1H NMR (400 MHz, DMSO) δ 9.92 (d, *J* = 8.2 Hz, 2 H), 8.24 (d, *J* = 12.4 Hz, 1 H), 8.01 – 7.88 (m, 2 H), 7.79 – 7.65 (m, 3 H), 7.46 (d, *J* = 3.1 Hz, 1 H), 7.32 (d, *J* = 3.5 Hz, 1 H), 3.88 (d, *J* = 16.7 Hz, 4 H), 2.50 (s, 6 H), 2.36 – 2.16 (m, 6 H) ppm. ^{13}C NMR (100 MHz, DMSO) δ 205.2(2), 151.0(2), 144.3, 143.3, 143.1, 142.6, 141.5, 139.9, 139.3, 139.1(2), 134.9, 134.7, 128.4, 128.3 127.0, 126.8, 125.9, 125.6, 123.6, 120.7, 118.6, 114.1, 113.9, 34.3, 34.0, 32.3(2), 19.7(2) ppm. HRMS (EI) calc. for [$C_{32}H_{26}O_4$]: 474.1831, found: 474.1832; IR (neat): 3455 cm^{-1} (OH), 1720 cm^{-1} (C=O); M.P.: 257 ^oC; light yellow solid.

3'aa: ^1H NMR (400 MHz, $CDCl_3$) δ 7.50 – 7.41 (m, 2 H), 7.34 – 7.24 (m, 2 H), 6.48 (s, 1 H), 6.18 (bs, 1 H), 3.64 (s, 2 H), 2.65 (s, 3 H), 2.22 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 209.8, 152.3, 143.8, 139.8, 138.5, 133.2, 129.8, 127.1(2), 126.9, 125.3, 121.8, 115.7, 33.2, 33.0, 18.7 ppm. HRMS (EI) calc. for [$C_{16}H_{14}O_2$]: 238.0994, found: 238.0996; IR (neat): 3365cm^{-1} (OH), 1693 cm^{-1} (C=O); M.P.: 136 ^oC; yellow solid.

4aa: ^1H NMR (400 MHz, $CDCl_3$) δ 13.70 (bs, 1 H), 7.81 (d, *J* = 7.6 Hz, 1 H), 7.57 – 7.46 (m, 2 H), 7.44 – 7.36 (m, 1 H), 3.58 (s, 2 H), 2.17 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.5, 177.6, 147.6, 138.3, 132.8, 127.4, 125.8, 123.2, 110.5, 30.3,

21.1 ppm. HRMS (EI) calc. for [$C_{11}H_{10}O_2$]: 174.0681, found: 174.0682; IR (neat): 3454 cm^{-1} (OH), 1762 cm^{-1} (C=O) ; M.P.: 73 ^oC; light yellow solid.

5aa: ^1H NMR (400 MHz, $CDCl_3$) δ 16.79 (s, 1 H), 7.58 (d, *J* = 7.1 Hz, 1 H), 7.46 – 7.32 (m, 3 H), 3.88 (s, 2 H), 2.38 (s, 3 H), 1.92 (s, 6 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$) δ 195.8, 190.4, 146.8, 144.6, 143.3(2), 128.8, 127.4, 124.6, 122.5, 106.8, 39.1(2), 29.7, 23.7 ppm. HRMS (EI) calc. for [$C_{16}H_{16}O_3$]: 256.1099, found: 256.1096; IR (neat): 3462 cm^{-1} (OH), 1715 cm^{-1} (C=O); M.P.: 113^oC; yellow solid.

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국 문 초 록

고분자 N-헤테로고리 카빈과 염기촉매를 이용한 유기반응의 연구

제 1부. N-헤테로고리카빈을 이용한 촉매 반응

제 1장

효율적이고 재사용 가능한 고분자(4-바이닐이미다졸륨) 아이오다이드를 이용하여 벤조인 축합반응을 온화한 조건에서 연구하였다. 고분자(4-N-고리형 카빈)은 단분자 형태보다 더 높은 촉매 활성을 보였고, 7번의 재사용에서도 촉매의 활성을 잃지 않았고, 성공적으로 회수하여 재사용이 가능했다.

제 2장

고분자(4-바이닐이미다졸륨)과 염기, 루이스 산을 도입하여 이산화탄소를 고정하는 효율적인 촉매 시스템을 구축하였다. 이 촉매 시스템을 통해 터미널과 인터널 에폭사이드를 이산화탄소와 반응시켜 고리형 카보네이트를 합성하였다. 다양한 작용기에서도 변형 없이 진행되었고, 입체성

이 있는 시작물질을 사용하였을 때, 같은 입체 구조를 가진 생성물을 얻었다. 고분자 촉매는 쉽게 회수되어 재사용하였다.

주요어. 고분자(4-바이닐이미다졸륨), 유기촉매, 재사용, 벤조인, 이산화탄소 고정, 고리형 카보네이트

제 2부. 염기 촉매를 이용한 유기반응

제 1장

인산 칼륨을 염기 촉매로 사용하여 아민과 에폭사이드 그리고 이산화탄소를 통해 옥사졸리딘온을 합성하였다. 대기압의 이산화탄소를 사용하고, 다양한 종류의 아민을 사용하여 반응하였다. 방향족 이소시안산염과 아미노 알코올이 중간체로, 이 반응을 통해 다양한 에폭사이드와 아민이 활용 가능했다. 다음의 원팟 반응은 높은 수율과, 단순한 실험과정, 저렴한 촉매를 이용하고 높은 스케일에서도 좋은 결과를 보였다.

제 2장

염기 촉매를 이용하여 원팟, 도미노 반응을 통해 비대칭 구조의 플루오렌 구조를 합성법을 개발하였다. 합성은 단순한 시작물질인 방향족 다이알데하이드와 다이카보닐 구조를 이용하였고 이를 통해 다양한 고리구조가 연결된 다환 방향족 탄화수소 구조를 합성하는 새로운 반응법을 개발하였다.

주요어. 염기 촉매, 인산칼륨, 원팟 반응, 도미노 반응, 비대칭 플루오렌, 이산화탄소 고정, 옥사졸리딘온

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